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ORIGINAL ARTICLES.

The Spherulitic Ironstones of West Yorkshire.

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(PLATE IV.)

Introduction.

THE Millstone Grit and Coal Measure rocks of West Yorkshire include a series of sedimentary ironstones characterized by the spherulitic habit of the siderite. These rocks have been examined in detail in Airedale and Calderdale, and in brief visits to East Lancashire and South-West Yorkshire the author has recognized a similar development of ironstones, and so believes that the substance of this paper may be generally applicable to the whole of the central and southern Pennine region.

During recent years while much work has been done on the iron-silicate ores, the carbonate ores have received far less attention. The works of Hallimond (1)[1] and Tomkeieff (2) contain the most recent views on the Coal Measure clay-ironstones, and Spencer (3) has described and discussed spherulitic carbonates from various British and foreign localities. Spencer's conclusions, drawn from rocks from several horizons and areas, were of a general character, and the present localized study has naturally allowed of a more detailed interpretation of local application, in some points resembling and in others differing from Spencer's interpretations. It may be mentioned that the spherulitic ironstones are at present of practically no value as ores, being only occasionally sold with ordinary clay-ironstones extracted incidentally in the working of brick clays and fireclays. On the other hand they are often a source of trouble in the working of fireclay, for they must be carefully removed if the fireclay is to be of any value as a refractory, and in some cases their abundance in the lower part has restricted the working of a fireclay to the upper part. The purpose of the present paper is to draw attention to the occurrence of spherulitic rocks marking a distinctive facies of Upper Carboniferous sedimentation in West Yorkshire, and to attempt to explain their origin.

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[1] Figures in parentheses refer to References at end of article.

OCCURRENCE.

The term spherulitic ironstone is used to cover a number of rock types, the commonest of which is bedded or nodular sphaerosiderite, but also including fireclays, mudstones, sandstones, and chamosite ironstones containing spherulites of siderite, or more rarely of pyrite replacing siderite. Associated with them are certain non-spherulitic ironstones, generally compact nodules of extremely irregular form. The long sinuous form of an extreme variety of the latter, common in underclays, strongly suggests that they represent the infillings of the courses of rootlets and so these will be referred to as root-nodules.[1] Root-nodules, however, are usually very minutely spherulitic.

In the Pennine area these rocks are found only at the base of, or more usually immediately below, beds of underclay above which coal seams may or may not occur. At any one horizon their distribution is always sporadic, but they have been found developed to various degrees in association with the majority of underclays between the Kinderscout Grits and the Better Bed coal. The local geological literature contains no references to spherulitic ironstones, and thus it is necessary to describe in some detail what are locally very commonplace sections. The occurrences are described in stratigraphical order below.

The Kinderscout Grits.—At the Snail Green boring, Rombalds Moor, sphaerosiderite occurred in a series of underclays and fireclay-mudstones extending upwards from 66 feet below the *R. reticulatum* mut. *a* band. The series was :—

ft.	in.	
5	0	Grey shale with plant remains.
6	0	Light grey fireclay with rootlets, root-nodules, and sphaerosiderite nodules.
2	0	Fine-grained grey sandstone, quickly weathering green.
4	0	Grey fireclay with vertical bands of sphaerosiderite.
6	0	Shaly fireclay-mudstone with sphaerosiderite bands and nodules.

The occurrence of sphaerosiderite in vertical bands has not been noted elsewhere, except on a minute scale. The bands were from 1 to 3 and 4 inches wide, from 9 to 24 inches deep, and while their lateral extent could not be seen, one passed right across the 18 in. core. The nodules were small, mostly about 3 inches in diameter, and the horizontal bands were thin.

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[1] This term is already in use for the bacterial growths on the roots of leguminous plants, but it would be difficult to confuse the two meanings.

The Middle Grits.—The underclay series of the Morton Bank coal at the Snail Green borings showed the following section :—

ft.	in.	
	9	Coal.
6	0	Light fireclay, full of rootlets, root-nodules (sometimes spherulitic), and compact irregular nodules.
1	0	Dark grey shaly fireclay-mudstone with strings and patches of siderite spherulites.
5	3	Alternations of thin dark shales with plant remains and fine-grained sandstones ; in both occur nodules and bands of ironstone of micro-organic origin.

Traces of this micro-organism occur in sections of the spherulitic rock, and apart from land plants are the only evidence of organic remains yet found in the spherulitic ironstones (see below, p. 53).

Associated with the coal seam below an *R. reticulatum* mut. β band which, however, is in the usual position of the mut. γ band, in Nan Scar Beck and Harden Clough, Oxenhope, is the following section :—

0 to 2 in.	Coal.
4 to 11 in.	Ganister.
0 to 2 ft.	Crumbling gritty sandstone, rather micaceous, with small patches of sphaerosiderite and isolated spherulites.
6 ft.	Sandstone (base not seen).

Spherulitic siderite is also developed at this horizon in the Ramsbottom and Darwen areas of East Lancashire, where the base of the underclay above the thick series of " siliceous ironstones " (4) is richly spherulitic.

The Rough Rock Shales.—The coal seam which occurs about 30 feet below the *G. cancellatum* marine band in the area north of the Calder to Rombalds Moor has yielded spherulitic ironstones at several localities. The greatest development was seen in the following sections at the Snail Green borings, which also shows their characteristically variable thicknesses.

B.H. No. 1.		B.H. No. 2.		(The borings are 50 feet apart.)
ft.	in.	ft.	in.	
1	6	1	6	Shaly coal.
2	6	2	6	Underclay with spherulitic root-nodules.
6	0	3	6	Brown fireclay-mudstone with irregular bands of green sandstone.
26	0	21	6	Richly spherulitic fireclay-mudstone with thin bands of green sandstone.

At the Bingley Brick & Tile Co's quarry the same series is well exposed, and shows the typical lateral and vertical variations between bedded sphaerosiderites in large nodules or lenticular bands, spherulitic fireclay-mudstones, and green sandstones. At Nab Scar, Oxenhope, and Wamesley Scar, Mixenden, nodules of sphaerosiderite occur below the underclay and micaceous sandstones are sometimes sparsely spherulitic.

The Lower Coal Measures.—Below the Cottingley Crow coal in

Cottingley Beck is exposed a variable series of ferruginous fireclay-mudstones and green sandstones. The underclay, 4 to 6 feet thick, is of a soft fireclay type, and at the base is a band of green chamosite nodules containing from very small to very large proportions of spherulitic siderite.

The fireclay of the Soft Bed coal has been worked at Lepton and at New Mill, both near Huddersfield, and contained abundant small ironstone nodules, sparsely and minutely spherulitic.

The Halifax Hard Bed fireclay is worked at Siddal (Halifax), and at High Birks, Thornton, and at both localities the lower part contains sphaerosiderite nodules and root-nodules in which the siderite is largely replaced by pyrite. Outcrop workings of the Hard Bed fireclay at Wappy Springs, Lindley Moor, show a band of ironstone from 2 to 5 inches thick below 3 feet of fireclay. The ironstone consists of spherulitic siderite set in a base of chamosite and sandy clay.

Associated with the underclay series of the 36 Yards Band and Hard Bed Band coals is a widespread development of spherulitic ironstones. West of Bradford at Brooke's and High Birks fireclay pits, Thornton, the pit heaps contain large quantities of sphaerosiderite. At Brooke's pits the section is :—

9 in.	Coal.
2 ft. 6 in. to 3 ft.	Fireclay.
2 ft. to 4 ft.	" Bottoms clay "—an impure fireclay largely composed of hard concretionary sphaerosiderite.

Around Elland the fireclay of the 36 Yards Band coal contains small sphaerosiderite nodules, and also compact non-spherulitic septarian nodules infilled with a clay mineral, while the " seggar clay " of the underlying Hard Bed Band coal often contains large nodules and lenticular masses of sphaerosiderite. At Beacon Hill, Halifax, and Ashday, Elland, the 36 Yards Band stone which underlies the fireclay is often richly spherulitic in its upper part.

In the Better Bed fireclay mined by Huddersfield Collieries, Ltd., at Lepton, sphaerosiderite nodules are fairly common.

The Middle Coal Measures.—These measures have only been examined cursorily for spherulitic ironstones, but although less conspicuous, there seems to be a similar development to that in the lower beds. They were found in the fireclay mined at Cumberworth (Whinmoor group), and below the coal 12 feet above the Top Haigh Moor coal at Robin Hood quarries near Wakefield.

PETROGRAPHY AND CHEMICAL ANALYSES.

I. *Lithology and Megascopic Characters.*

The spherulitic ironstones usually occur in rocks of the underclay or fireclay-mudstone type. The latter (4) is normally a greyish rock, rather tough, and with only a very crude lamination. Almost invariably associated with them are thin bands of fine-grained green sandstone.

The sphaerosiderite nodules vary in size from about 2 inches in diameter to ovoid masses 2 feet or more in length, grading into lenticular masses up to 8 or 10 feet in length and 1 to 2 feet thick. They are typically loaf-shaped, showing far less vertical compression than the normal Coal Measure nodules. Their colour varies, usually from buff green to grey green, but a greenish tint is characteristic in contrast with the prevalent browns of the normal ironstones. The surface is always rough on account of projecting spherulites and never shows the smoothness and laminated skin of the normal nodules. Septarian structure is not developed, the nearest approach to it being rare and very thin cracks lined with a very faint film of metallic sulphide (galena ?). Septarian nodules, infilled with botryoidal siderite, calcite, or a clay mineral (kaolinite or dickite ?), sometimes occur with the spherulitic ironstones but are themselves non-spherulitic. Some spherulitic nodules from Cottingley Beck, however, show a peculiar system of concentric partings with striated surfaces sometimes lined with galena, which is perhaps a septarian structure later modified by a yielding of the rock and the production of slickensiding on the surfaces of the septarian cracks.

When the spherulites are disseminated through a fireclay-mudstone without segregation into nodules, as in the Rough Rock Shales at Snail Green, where they make up 30 to 40 per cent of the rock, the crude lamination of the mudstone becomes even more indistinct. Rootlets, from $\frac{1}{8}$ to 1 inch in diameter, sometimes pass through the nodules. They consist either of ironstone, usually much more minutely spherulitic than the surrounding nodule and exactly similar to the ironstone root-nodules, or are infilled with silica, a clay mineral (kaolinite or dickite), or calcite, without, however, preserving the structure of the rootlet.

In the fireclay-mudstones and associated rocks animal remains are conspicuously absent. The ironstone referred to above (p. 51) as being of micro-organic origin is difficult to interpret, but it appears as though it might have been produced by the secretions of some minute burrowing organisms which lived in colonies in the sand. Plant remains occur but not in any great quantity, and consist mainly of stigmarian rootlets.

II. MICROSCOPIC CHARACTERS.

A. The Spherulites.

Their characteristic feature is the radial structure, indicated by the black cross produced between crossed nicols. When viewed over the polarizer they show a prominent relief brush (birefringence of siderite ·241) which is always perpendicular to the vibration direction of the polarizer, indicating that the siderite fibres are elongated paralled to the *c* axis. In a given rock the spherulites tend to be more or less uniform in size. The smallest spherulites occur in root-nodules, often averaging ·1mm. in diameter. In the sphaerosiderite nodules they range from ·2 mm. (e.g. Kinderscout, Snail Green) to the largest spherulites found, 3 to 5 mm. in diameter, in chamosite nodules from Cottingley Beck. The usual size is from ·5 to 1 mm., most frequently about ·7 mm. The character of the surrounding medium appears to control the degree of perfection of spherical shape of the spherulites. In a homogeneous medium such as a fireclay-mudstone or a pure fireclay, the spherulites assume an almost perfect spherical form, or when crowded together and mutually interfering, are regularly polygonal. In more heterogeneous rocks, such as sandstones, ganisters, or sandy fireclays, they are often considerably malformed.

The spherulites are built up of narrow fibrous crystals radiating from the centre. Normally the component fibres are visible in ordinary light, but in certain types (e.g. Rough Rock Shales, Snail Green) the spherulite is apparently composed of a mosaic of siderite rhombs, the true radial structure only being recognized by the black cross between crossed nicols. Sometimes the component fibres are fewer and broader, and in the extreme only two, three, or four crystals are seen in sections. On the other hand the fibres may be very fine indeed, and those in the large spherulites from Cottingley Beck, for example, cannot be resolved with the usual high power objective. A fairly common feature in spherulites from the Bingley quarry is the formation between crossed nicols of two black crosses, slightly overlapping, indicating that the fibrous crystals radiate from two centres. When two spherulites of unequal size are in contact their surface of separation is nearly always concave towards the smaller individual, more rarely almost a plane surface. Spencer (3) found the same relationship in all the spherulitic carbonates he examined, and showed that this was the form to be expected from two spherulites growing by crystallization from a supersaturated medium.

The nucleus from which the spherulite has grown is never visible. Although quartz grains are commonly included within the spherulites they never appear to act as nuclei. Another type of nucleus—not, however, a nucleus of crystallization—is frequent. It is often seen that the black cross produced between crossed nicols does not extend to the centre, and that the central area remains uniformly illuminated when rotated between crossed nicols. This would suggest that the spherulite has grown about a small globule of cryptocrystalline siderite. In certain cases this nucleus could be measured, and the following results are typical :—

Diameter of spherulite in mm. .	·77	·65	·65	·81
Diameter of nucleus in mm. .	·19	·18	·16	·12

This cryptocrystalline nucleus appears to be analogous to the finely granular material which occupies the centre of nodules of radially fibrous pyrite described by Bannister (5) from the Chalk.

Sediment is always included within the spherulites. It consists firstly of recognizable minerals, almost entirely of angular quartz of relatively large size, ·05 to ·1 mm., and rarely flakes of muscovite, and secondly of finely divided argillaceous or carbonaceous material which clouds the siderite and may render it almost opaque. While the quartz grains are always irregularly distributed in the spherulites the finer sediment usually bears some relation to the structure of the spherulite. Most usually it is only included at the centre, where it may occupy up to half the diameter of the spherulite ; but the reverse is seen in root-nodules from the Bingley quarry in which the spherulites consist of a central portion of clear siderite surrounded by a ring almost completely masked by radially distributed opaque carbonaceous matter. Zoning of the finer sediment is quite common, but there is seldom more than one zone. Spherulites from below the Morton Bank coal at Snail Green are very conspicuously zoned (Pl. IV, Fig. 3), but this is exceptional, the zones being usually very faint. By Spencer's method of leaching out the carbonate (3, p. 673), however, the zones may be clearly displayed. In such leached sections the zone appears as a ring of finely granular matter, often accompanied by radially distributed grains indicating that the sediment was also expelled laterally from the fibres of siderite. In general the sediment is included within the spherulites, either between the fibres or as a zone, and is not expelled to the margin since the contact surface of interfering spherulites is usually quite free from sediment. The zoned spherulites from Snail Green (Pl. IV, Fig. 3), however, are noteworthy exceptions to this generalization.

Many spherulites show faint concentric zones of slightly different tints, between pale yellow brown and grey, and in reflected light this zoning becomes quite distinct and is often recognizable in sections which in transmitted light appear uniform throughout. By reflected light the different zones show different shades of white and grey. Two or three zones are the most frequent—a central light area, a darker zone, and an outer light zone—but sometimes four or five zones are visible. In some cases the cryptocrystalline nucleus consists of an inner darker and an outer lighter zone, and the outer radial portion is also zoned. The boundaries between the zones are seldom sharp, and in the outer zones there is a gradual transition from light to dark. The zones appear to consist of carbonates of slightly different compositions. So far the carbonate has always been referred to as siderite, but analysis shows that other carbonates are present. Siderite, magnesite, and calcite are all present, in the ratios of approximately 88 : 8 : 4 respectively, and being partially isomorphous a series of solid solutions of different compositions is possible, which if zoned might produce the reflection zones described above. By staining the sections lightly with hydrogen peroxide (Hallimond's method (1), p. 39), the zoning was sometimes accentuated in tones of brown corresponding to different iron contents, confirming this explanation.

Secondary changes in the spherulites generally appear to commence at their centres. Quite frequently a small reddish oxidized area occurs at the centre and from it three or four oxidized cracks may radiate. The replacement of carbonate by pyrite is seen in different stages from the appearance of small grains of pyrite at the centre to a stage in which the spherulite consists almost wholly of pyrite but includes patches of carbonate with fretted borders and has an outer fringe of carbonate. The replacement appears to proceed radially for at an intermediate stage the pyrite occurs as feather-like radial projections into the carbonate. Cleavage lines often continue through two patches of carbonate now separated by pyrite.

By weathering the spherulites are altered to limonite, and all stages can be traced from colourless siderite to red powdery limonite. The spherulites may be uniformly stained to a brown tint, or have a highly oxidized skin while the inner portion is relatively fresh (Pl. IV, Fig. 1). The thickness of this skin in a given rock is independent of the size of the spherulites, and in those from the Rough Rock Shales at Snail Green is nearly always between ·04 and ·06 mm.

B. The Ground-mass and Associated Sediments.

The base in which the spherulites are set may consist of ironstone, sideritic or chamositic, or of any form of underclay or other sediment such as occurs associated with underclay. In sparsely spherulitic ironstones the non-spherulitic siderite is usually coarsely crystalline, its crystal size ranging up to ·2 mm., and thus distinctly coarser than the crystals of the normal clay ironstones which average ·01 mm.

The discovery of chamosite in the spherulitic ironstones was rather unexpected in view of the conclusions of previous workers. Hallimond (1, p. 63), referring to the clay ironstones of the Coal Measures, states: " The Coal Measure ores rarely yield even 1 per cent of soluble alumina, and this was probably derived from the clay; the analyses therefore establish conclusively the substantial absence of chamosite from the present group of rocks." Spencer (3, p. 691), states, " it would appear that the absence of the green silicate mineral (chamosite) has been essential to the formation of the spherulitic form of siderite, and its presence necessary for the development of the oolitic variety." Chamosite, however, forms the bulk of many of the nodules from Cottingley Beck, a specimen analysed containing 70 per cent of this mineral, is a notable constituent of the Wappy Springs ironstone, and appears in small quantities in many of the thin sections of the spherulitic ironstones. In the richer nodules (Pl. IV, Fig. 5) it appears as a felted aggregate of rather stout mica-like flakes, up to ·02 to ·03 mm. across, showing a fairly distinct basal cleavage. The colour is light pea-green, and pleochroism is fairly distinct, deep green for vibrations parallel to the cleavage and light green for vibrations perpendicular to the cleavage. The refractive index, determined on crushed material by the immersion method, is about 1·63; the double refraction is less than that of quartz and the mineral often appears almost isotropic. A calculation of the density from the rock density and mineral analysis gave a value of 3·14. These characters together with the chemical analysis (below, p. 58) appear to prove beyond doubt that this mineral is chamosite. Associated with the chamosite are flakes of a similar chloritic mineral, which, however, is distinctly brown in colour. Unfortunately it did not occur in sufficient quantity to be separated easily, and so its characters and composition could not be determined.

The diversity of character of the sediments in which spherulites occur is remarkable. They occur in all types of underclay and sandstone, fine or coarse, micaceous or ganister-like. In the coarse sandstones the spherulites accommodate themselves between the quartz grains, sometimes appearing as discontinuous segments or sectors between three or four quite large grains. The spherulites are larger in the finer sandstones, up to ·8 mm. for example in a ganister, but only ·2 mm. in a coarse sandstone of grain-size ·4 to ·7 mm. In these sandstones, just as in all underclays, the felspathic and ferromagnesian minerals are completely decomposed. In the sphaerosiderite nodules the interstitial sediment, usually of a fine arenaceous fireclay type, is generally almost free from iron compounds, as shown by its light colour when roasted, but in spherulitic fireclay-mudstones segregation has often been less complete and the clay base turns red when weathered or roasted.

The green sandstones are of interest in that their coloration is seen to be due to the alteration of the felspathic and ferromagnesian constituents to chlorite, with quite frequently the formation of chamosite. Quartz and muscovite alone resist alteration. All stages can be seen, from chlorite replacing such a mineral as biotite and obviously retaining the structure of the latter, to clear chlorite, identical with the chamosite of the ironstones, which could only have been formed by reactions involving complete solution of the original mineral and subsequent crystallization as chamosite.

III. CHEMICAL ANALYSES.

The ironstones were dissolved in semi-normal hydrochloric acid and the soluble constituents thus separated from a residue which represents practically the sediment associated with the authigenic carbonates or chlorite. Unfortunately, Analyses I and III had been completed before chamosite had been recognized in these rocks, and consequently their soluble silica, perhaps present in small quantity, has not been estimated.

ANALYSES.

	I	II	III	IV
SiO_2	n.d.	66·37	n.d.	17·93
TiO_2		·99		
Al_2O_3	4·60[1]	21·98	·05	17·57
Fe_2O_3		1·38	1·41	2·20
FeO	35·25		45·84	32·34
MnO	n.d.	n.d.	tr.	tr.
CaO	1·68	1·03	1·70	·05
MgO	2·51	·98	3·40	3·86
K_2O		·90		
Na_2O		·14		
CO_2	25·64[2]		33·12[2]	5·05
$H_2O +$		7·78	·50	6·91
$H_2O -$	·13		·83	·47
Residue	30·24[3]		10·69[4]	15·52[4]
Total	100·05	101·55	97·54[5]	101·90
Sp. Gr.	3·25		3·51	3·05

I. Sphaerosiderite nodule, Bingley Brick & Tile Co's quarry.
II. Silicate analysis of insoluble residue (dried at 110° C.) of No. I.
III. Spherulites isolated from the fireclay-mudstone of the Rough Rock Shales, Snail Green boring No. 1.
IV. Green chamosite nodule, sparsely spherulitic, Cottingley Beck.

The mineral compositions of the ironstones, calculated from the analyses, are tabulated below. In the case of No. IV both iron and magnesia are distributed between carbonate and chamosite, and so the assumption was made that the carbonate contained 88 per cent $FeCO_3$ and 8 per cent $MgCO_3$ as in Nos. I and III.

	I	III	IV
Siderite	56·84	73·92	11·75
Magnesite	5·24	7·11	1·07
Calcite	3·00	3·03	·08
Chamosite	?		70·55
Limonite	4·60	1·57	2·45
Remaining oxides		·39	
Residue and moisture	30·37	11·52	15·99

The composition of the carbonate is very similar to that of the mineral, frequently spherulitic, described as sideroplesite from the

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[1] Probably contains some SiO_2 and indicates a little chamosite.
[2] Calculated.
[3] Dried at 110° C.
[4] Ignited.
[5] Total low, partly because carbonaceous matter conspicuous in thin section was not estimated.

Glenboig fireclay (6). This similarity is shown by expressing the individual carbonates as percentages of the total carbonate.

	$FeCO_3$	$MgCO_3$	$CaCO_3$
No. I . . .	87·3	8·1	4·6
No. III . . .	87·9	8·5	3·6
Glenboig sideroplesite .	88·4	8·3	3·3

In view of the isomorphism which exists between the carbonates and the fact that the spherulites contain zones of carbonates of different composition, reference to a mineral species is not justifiable.

From No. IV the composition of the chamosite could be calculated :—

	SiO_2	Al_2O_3	FeO	MgO	H_2O
Percentage weight .	17·93	17·57	25·05	3·35	6·66
Molecular ratios .	200	115·5	234·5	55·9	125

These ratios correspond to a formula approximating to $2SiO_2 . Al_2O_3 . 3(Fe,Mg)O . nH_2O$.

The 11 per cent residue of the isolated spherulites is represented mainly by sediment included within the spherulites, and this is probably quite a typical value, although in spherulites clouded or opaque with sediment the value must be very much greater. On the other hand the inner portion of a minutely spherulitic root-nodule yielded on partial analysis only 5 per cent of residue, and this represented almost entirely by organic matter. This low value is easily understood if the root-nodules are interpreted as infillings of root-moulds by siderite (in this case 88 per cent of the rock) and the other carbonates. The sphaerosiderite nodule No. I occurred in a fireclay-mudstone, and so it may be assumed that the composition of its insoluble residue, No. II, is practically that of the fireclay-mudstone. If Analysis II is compared with analyses of normal Coal Measure shales and of underclays of the fireclay type, noting particularly the contents of alkalies, water, and titania, it is seen to be roughly intermediate between the two types. While analyses do not appear to be available, microscopic examination shows that fireclay-mudstones represent intermediate stages in the alteration of fine shales or mudstones into underclays, and thus Analysis II is rather what would be expected in a fireclay-mudstone.

A comparison of these analyses with those of normal Coal Measure clay-ironstones of the district brings out certain differences. The normal ironstones have a higher lime content, from 2 to 6 per cent, and in general a lower magnesia content, ranging up to 3 per cent but averaging only 1 per cent, whereas a partial analysis of a spherulitic nodule from Cottingley Beck gave 5·2 per cent magnesia. As yet chamosite does not appear to have been recognized in the normal clay-ironstones, and so if it is essentially absent its presence in some of the spherulitic ironstones forms another point of contrast. Perhaps the most striking difference is seen in the alkali content of the insoluble residue. The residues of normal clay-ironstones " are rich in alkali, containing from 2 to 4 per cent of potash " (Hallimond (1), p. 65), whereas the sphaerosiderite residue only contains ·9 per cent potash. The significance of these differences will be discussed in dealing with the origin of these rocks.

THE ORIGIN OF THE SPHERULITIC IRONSTONES.

In discussing the origin of these rocks there are two main problems to consider. Firstly, the mode of formation of beds of ferrous carbonate and chamosite, and secondly, the origin of the spherulitic habit of the carbonate. Further, the theory adopted must explain the differences between these rocks and the normal Upper Carboniferous ironstones.

I. *The Origin of the Ferrous Carbonate.*

At many localities the ironstones consist of but a few scattered nodules, so that the beds in which they occur, if considered as a whole, contain no more iron than is normally found in shales and underclays. On the other hand certain quite thick beds are extremely rich in ironstones, and these must have required the precipitation of relatively large quantities of iron for their formation. Bearing in mind the essential associations of these ironstones, i.e. that they only occur below beds of underclay, two possible periods of precipitation suggest themselves.

(1) The iron was precipitated as a phase of the sedimentation prior to the formation of the underclay.

(2) The iron was precipitated in the sediments from solutions which percolated through them during the formation of the underclay, perhaps from an overlying coal-swamp.

There is little evidence in favour of the second theory. Underclay formation (see below) may involve the redistribution of iron minerals but not their introduction, and there is no evidence that the coal-swamps were iron-swamps. The first theory is thus adopted.

Before inquiring further into the mode of precipitation of the iron it will be well to consider the physiographical conditions under which precipitation must have occurred. The upper Millstone Grits and Ganister Series of the Coal Measures show a rhythmic sequence of sedimentation. The phases of the rhythm, as recognized by the author, are tabulated on p. 61.

The rhythm tabulated is the ideal one, which is seldom fully developed in any one area or horizon. The recognition of this ideal rhythm, however, greatly aids the interpretation of the imperfect rhythms seen in the field. In the strata under consideration this rhythm is repeated some fifteen times in a thickness of 1,500 feet of rocks, and the present investigations have shown that spherulitic ironstones occur in nine of these rhythms.

The materials of the spherulitic ironstones are seen to have been deposited during the final silting-up stage of the rhythmic sedimentation. During these final stages shallow lagoons would be formed, rich in vegetation, in which the fine sediments of the fireclay-mudstones and green sandstones were deposited. Iron was brought on to the shallowing delta in the waters of the Great River of the Millstone Grit, probably in the form of a ferric oxide hydrosol, for Moore and Maynard (7) have shown that it is in this form that the greater part of the iron in river waters is carried. Here, as the land surface was built up, the water would become partially enclosed in the lagoons, stagnant and rich in plant life. Under these conditions biochemical reactions cause the reduction of the ferric oxide with the formation of ferrous carbonate or bicarbonate. Following Hallimond (1), who treats the precipitation of ferrous carbonate from the standpoint of solubility product, two factors can be recognized which would favour precipitation. Firstly the reduction might liberate ferrous ion (Fe^{++}) in relatively large quantities, which in presence of normal amounts of carbonate ion (CO_3^{--}) would cause precipitation, and secondly in the lagoons the water was probably quite warm and consequently the relatively high degree of dissociation of the bicarbonate would yield a high concentration of carbonate ion. Further the fine sediments were probably precipitated in a semi-colloidal state and thus capable of absorbing ferrous carbonate which later, on flocculation of the precipitate and the elimination of water, would reach supersaturation. The importance of the latter factor is difficult to estimate, but as the sediments are no finer than those associated with the normal clay-ironstones, it would not appear to have been exceptional, and cannot alone account, as Spencer suggests, for the spherulitic character of the carbonate.

Lithology	Flora and Fauna	Movements and Sedimentation
Coal	Terrestrial	Land Surface, Sedimentation Suspended.
Underclay		
Fine Sediments with spherulitic ironstones.		Sedimentation in Excess of Subsidence.
Sandstone		
Grey Shale	Modified Marine: *anthracoceras* dominant.	
Blue Shale with Marine Band and clay-ironstones.	Marine: *Gastrioceras* or *Reticuloceras* dominant.	Maximum of Subsidence.
	Estuarine: fish and non-marine lamellibranchs.	Subsidence in Excess of Sedimentation.
Coal	Terrestrial	Land Surface.

II. *The Completion of the Sedimentary Rhythm and the Origin of the Spherulitic Structure.*

Having suggested how the ferrous carbonate was deposited, the sedimentary rhythm must now be followed to its close and the conditions sought which might have given rise to the spherulitic structure. The final stages consist of the gradual silting up of the lagoons and the formation of the underclays. Underclays have generally been interpreted as representing soils developed by the plants of the coal swamps. Recently, however, Weller (8), confirming the earlier work of Stout (9), has shown " that underclays represent weathering profiles produced by long continued exposure to atmospheric agencies ", in particular " the leaching and oxidizing action of descending ground waters ". Coal formation, on the other hand, requires stagnation of drainage and lack of oxygen, and so while coal may later develop on the underclay it does not produce the underclay. All the evidence from the Millstone Grit and Lower Coal Measures of West Yorkshire appears to support this interpretation, and so it is the one accepted by the author. Accepting this interpretation, a close analogy can at once be recognized between the spherulitic ironstones and the concretionary, pisolitic, or oolitic forms of calcium carbonate, limonite, bauxite, hydrated manganese oxides, etc., so frequently associated with residual deposits.

The form which the ferrous carbonate took when precipitated has not been indicated, but it is clear that as the sediments were soon to be brought immediately below a zone of weathering their original form would be quite temporary. As the underclay developed, whatever iron was present in the upper zone of leaching and oxidation would go into solution, probably as a ferric oxide hydrosol, and so descend to a lower zone of stagnation and reduction and there be reprecipitated as ferrous carbonate. Owing to the low relief of the land surface the zone of oxidation was probably very shallow, perhaps no deeper than the present underclay. In the great length of time required for the development of the underclay, however, climatic variations would cause the boundary of the zones to fluctuate, occasionally descending towards the base of the fireclay-mudstones and finally rising to the land surface when coal-forming conditions set in. It is thus probable that there was a considerable redistribution of the ferrous carbonate within the sediments.

The development of chlorite in the green sandstones and the formation of chamosite by reactions between ferrous solutions and the clay minerals, belong to this stage. The instability of chamosite in acid solutions is stressed by Hallimond (1), and so it may be inferred that while the solutions were probably rich in weak organic acids the concentration of carbonic acid was low enough to allow of the formation of chamosite.

In the absence of electrolytes and the abundance of protective organic colloids the ferrous carbonate would be precipitated from solution in colloidal form, and so could undergo segregation into nodules and bands in the manner described by Tomkeieff (2). This process leaves the nodules in the gel state, and it is crystallization from the gel that has resulted in the spherulitic habit of the carbonate. In this gel state the nodules probably resembled the concretions described by van Bemmelen (10) from the peat of Drenthe, Holland, which contained up to 90 per cent of colloidal ferrous carbonate protected by humic acids.

Recent work has shown (11) that substances of almost any chemical class and crystallizing in any system may be prepared in spherulitic form, but little is known of the factors controlling the formation of spherulites. While the best spherulites are generally grown in gels, they sometimes result from reactions in ordinary aqueous solutions, so that the gel, although highly favourable, is not essential for their formation. Artificial spherulites of ferrous carbonate may be prepared quite easily by allowing a solution of sodium carbonate to diffuse into a gelatine gel containing a dilute solution of a ferrous salt (the author used N/2 Na_2CO_3 and N/20 $FeCl_2$ in 10 per cent gelatine).

The author can only offer the following rather speculative explanation of the spherulitic growth of the siderite, and hopes that physical chemistry may soon yield a sounder theory based on definite fact. The ferrous carbonate gel would be highly viscous so that when crystallization set in, as eventually it must, the rate of crystallization would be very slow. To compensate for this the crystals would tend to grow as fine needles, for it has been shown that the rate of growth in a particular direction is inversely proportional to the area of cross-section (12). As is to be expected in siderite this elongation of the crystals occurs in the direction of the optic axis. At the centre of crystallization these fine crystals will at first be orientated in all directions, but as growth proceeds only those crystals whose optic axes are directed radially outwards can continue to grow, and so the radial structure develops around a cryptocrystalline nucleus. Such slow crystallization is bound to be periodic, and so will give rise to zones of carbonates of different composition corresponding to the different degrees of supersaturation required for their crystallization, and also to zones of sediment expelled during each period of crystallization.

Where the siderite is replaced by pyrite this must have occurred very shortly after the growth of the spherulites ; indeed, the fact that the pyrite occupies their centres suggests that replacement was almost contemporaneous with the formation of the spherulites. The most obvious source of sulphur for this pyrite is from the decay of proteid matter liberating hydrogen sulphide. In the case of the almost completely pyritized spherulites from below the Halifax Hard Bed coal, however, it may be mentioned that this seam is notably rich in pyrite which is probably due to the reduction of the sulphates of the brackish waters of the coal swamp which constitutes an intermediate reaction in the formation of its well-known "coal-balls" (13). If this is the case it indicates that the spherulitic ironstones were still in process of formation during the growth of the coal swamp, which is further made probable by the frequent segregation of sphaerosiderite nodules around rootlets that penetrate downwards from the coal seam.

THE RELATION OF THE SPHERULITIC IRONSTONES TO THE NORMAL CLAY-IRONSTONES.

The normal clay-ironstones, which occur above the coal seams, were precipitated during the subsidence phases of the rhythmic sedimentation and so have quite a different history. When first precipitated the materials of the spherulitic ironstones probably resembled closely those of the clay-ironstones, but whereas the latter are unaltered, the former were altered during the period spent in solution or as colloids prior to their consolidation. The low alkali content of the residue of the sphaerosiderite is undoubtedly due to the leaching action on the felspars, and the relative decrease in lime and increase in magnesia of the spherulitic with respect to the normal ironstones is probably due to a differential leaching action on the carbonates themselves.

The normal ironstones, while segregated in a colloidal state, probably crystallized relatively soon afterwards. The solutions which percolated through the sediments of the subsiding delta would become poorer in protective organic colloids, and eventually, by exhaustion of the latter higher in the sediments, would become electrolytic in character. Under these circumstances the gel state of the ferrous carbonate would be of short duration and probably never reached a very viscous state. Crystallization would thus follow normally without the development of the spherulitic structure.

In conclusion the author wishes to acknowledge the help received in the Department of Mineralogy and Petrology, Cambridge, where the laboratory work was carried out, and special thanks are due to Dr. F. C. Phillips for much assistance in the microscopical and analytical work. He is further indebted to Mr. J. A. Butterfield for the microphotographs.

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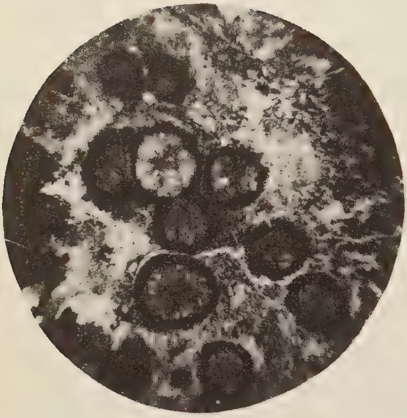

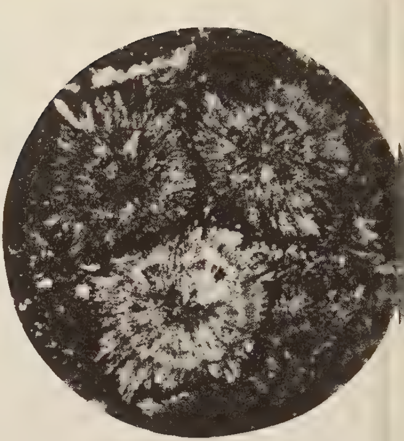

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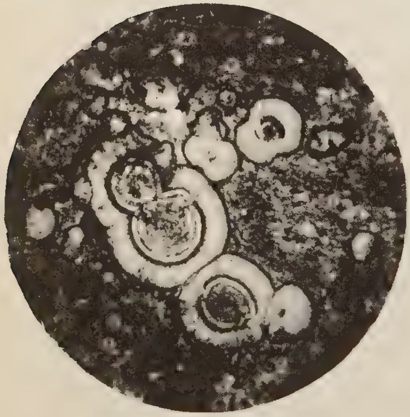

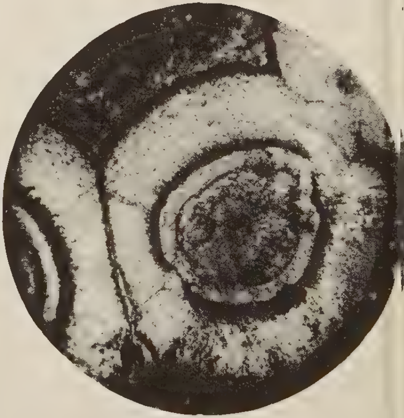

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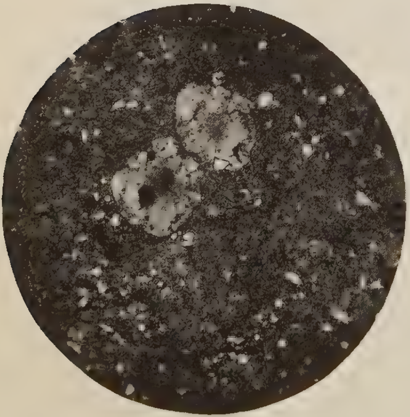

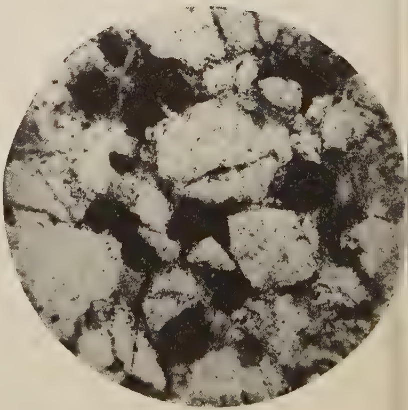

Spherulitic Ironstones from the Millstone Grit of Yorkshire.

To face p. 65.]

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EXPLANATION OF PLATE IV.

Fig.

1.—Spherulitic fireclay-mudstone, below Rivock Edge coal, Snail Green boring No. 1, Rombalds Moor. × 18 (slide 2). Spherulites with dark oxidized skins in a base of fine fireclay-mudstone.

2.—Sphaerosiderite nodule, below Rivock Edge coal, Bingley Brick & Tile Co's quarry. × 36 (slide 55). A typical section, showing zoning due to the combined effects of zones of carbonates of slightly different composition and zones of included sediment. The ground-mass is of a fine siliceous fireclay type.

3.—Spherulitic fireclay-mudstone, 6 feet below Morton Bank Coal, Snail Green boring No. 2, Rombalds Moor. × 36 (slide 63). Prominently zoned spherulites; the contact surfaces between the spherulites are concave towards the smaller individuals.

4.—The same as Fig. 3. × 120. The zone of included sediment is resolved into radial lines between the fine fibres. A marginal zone of sediment is seen at the contact of the two spherulites.

5.—Chamosite nodule with spherulites, 5 feet below Cottingley Crow coal, Cottingley Beck. × 36 (slide 59). The ground-mass consists of a felted aggregate of chamosite flakes. Angular quartz is conspicuous but all argillaceous material has been converted to chamosite. Small patches of pyrite are seen replacing the carbonate of the spherulites.

6.—Spherulites in coarse sandstone, 1 ft. 6 in. below coal, Middle Grits, Harden Clough, Oxenhope. × 36 (slide 45). The small partially oxidized spherulites occupy the interspaces between large quartz grains.

Significance of the British Quaternary Strand-line Oscillations.

By Cosmo Johns.

Introduction.

IT is proposed in this communication to describe the results obtained, and methods employed, in an investigation of the British strand-line oscillations and to discuss related episodes on the Continent. The original object was to determine the nature of the movements and, if possible, to discover their time relations, but the unexpected correlations that emerged rendered it necessary to extend the scope of the investigation. The data available include the pre-Glacial, 100-ft. and 25-ft. raised beaches together with the knowledge that the land stood high above the prevailing sea-level and was glaciated between the first and second beaches mentioned, and that there was a re-advance of the ice between the second and third. The most interesting feature of the oscillations is that they constitute a complete cycle ; for the sea which left the pre-Glacial beach at the beginning of Quaternary time, practically returned to it at the close. This cyclic nature of the movements suggested that if the first, or determining, movement could correctly be assumed, it should be possible to depict the changing relations of sea and land in a simple bi-axial diagram ; the movements being given absolute value by reference to the earth's centre.

The possible assumptions are limited to (*a*) movement of the land ; (*b*) variations in the ocean level ; or (*c*) a combination of these two. It is known by the principle of isostasy that the ice-load must depress the land, while the ice sheets can only grow by abstracting water from the sea. It is clear, therefore, that (*c*) must be partly true, but as those two movements are consequences of the glaciation they must be left for use only when they become operative. Thus in practice the choice is limited to (*a*) an uplift of the land, or (*b*) a lowering of ocean level as the determining movement, but it is recognized that the particular movement decided on will only be the effective part of a possibly complex series of movements due to a temporary distortion of the earth. It is not intended to discuss the nature of that distortion here.

II. The Raised Beach Curve.

The movements now being considered can be given absolute value by using the horizontal line X–Y in Fig. 1*c*, to represent the march of Quaternary time along the original level of the pre-Glacial beach. This line will always be at the same distance from the earth's centre, and thus provides a datum line in place of a datum point. It will be a further convenience, for the purpose of description, to divide X–Y into 100 parts so that any point on the time scale thus provided can be referred to as having occurred when a certain percentage of Quaternary time had elapsed. Thus any particular event can be described as having the date of Q. 45 or Q. 80, etc. Precision in statement will have been gained without any assumption as to the actual duration of the Quaternary age.

The first assumption made of the determining first movement was that there had been an uplift of the land, but it was soon seen that there would be serious difficulties in using it. Obviously the most important point to fix is the first intersection of the land and sea curves. This was found impossible except by assuming the very time value that we are seeking to discover. An uplift of the land, though not excluded as a possibility when, and if, relevant data become available, thus proved unworkable and had to be rejected. This left a depression of the ocean level for consideration with a rather wide choice of estimates as to its magnitude. It is clear that the Continental shelf was uncovered from the evidence of prolongation of fjords and land valleys on the adjoining ocean floor and this provides a minimum. Brögger's (1) estimate of 2,600 metres, based on the dredging from that depth of ocean of the shallow water Yoldia fauna, can be taken as maximum. It will probably be deemed an excess of caution to compromise by adopting an estimate of 1,000 metres for the ocean depression. Justification may be found in the earlier recognition that the apparent or effective movement is only a part of the distortion of the figure of the earth.

There is less difficulty in adopting an estimate of the average thickness of the ice sheet, for Penck (2) arrived at a value of 1,000 metres of which one-third is available for isostatic depression of the land when equilibrium is established. When a convenient scale has been selected for the vertical movements, the graph can be drawn (Fig. 1*c*). In the absence of any knowledge of the real cause of the movements, a difficulty that applies with equal force if treating an uplift of the land, the sea depression curve must be treated as symmetrical but with its lowest point shifted to the left at Q. 45, to allow for the abstraction of ocean water to form the land ice. The land curve is then drawn with due regard to the principle of isostasy. In view of the time that elapsed before the land curve is intersected by the sea curve rising with its upward swing, isostatic equilibrium must have been established. The first change of rate of rise of the sea, as distinct from the pendulum character of its vertical oscillation, occurs when it reaches the Continental shelf and proceeds to melt or float off the ice resting there. By the time the Irish and North Sea ice was reached, the sea would have gained a substantial return of formerly land-locked water with the result that the sea curve rises rather abruptly. At the same time the land is relieved of part of its load, but its response, depending on the viscous flow of deep-seated layers in the earth, will be sluggish compared with the rapid rise of the sea.

The submergence which follows is at its maximum depth near the commencement and lessens as the land rises with increasing velocity until a point is reached when sea and land are rising at the same rate. If this equal rate of rise is prolonged for a sufficient length of time, a beach or terrace will form where the ice-free coasts or submerged river valleys are bounded by rocks capable of receiving and preserving such an impression. It follows that raised beaches are formed when the rate of rise of both sea and land happened to be the same for a sufficiently long period to permit of beach formation. This condition of equal rate of rise might be repeated and a later beach formed.

The ultimate emergence of the land, rising faster than the sea, carries it high enough to re-establish glacial conditions. The renewed growth of the ice has the effect of slowing down the rise of the sea by abstracting water and may even have caused the rise to cease for a time. The land will, under its new ice load, seek its appropriate equilibrium until the sea, as it continues its upward swing, once more melts or floats off the ice and commences a second submergence, but this time on a smaller scale. There would be time between the removal of the low-lying ice and the advancing sea for the growth of forest and peat. The curves approach as sea and land meet, practically at the original pre-Glacial beach level, and with the final closing of the curves the cycle is complete.

A Quaternary temporary depression of the ocean level, of the order of 1,000 metres or more, is thus shown to be competent to give a rational description of the changing disposition of sea and land complete enough to enable maps to be prepared for any date in Quaternary time. It would, of course, be necessary to prepare graphs for selected points in the glaciated area to allow for differential depression of the land owing to the spatial variations in the thickness of the ice sheets and to determine the position of the strand-line from Admiralty charts.

The accuracy of the time values obtained, expressed as percentages of Quaternary time, will be discussed when they are compared with Penck's Alpine climate curve. When we come to deal with climatic changes, a simpler form of graph suffices, one that shows the relation of the land to the prevailing ocean level. This time-land elevation curve is given in Fig. 1*d*, where ocean level is used as datum line and the relative position of the land is obtained from the absolute raised beach curve. Stress must be laid on the derived character of this time-land elevation curve. Every quantity used, whether of time or relative position of sea and land, has been determined by, and derived from, the raised beach diagram.

III. Comparison with Penck's Climate Curve.

It is now possible to compare the raised beach graph with Penck's well-known Alpine climate curve, (3) using the same time scale for both. From Fig. 1 it can be seen that an unexpected relationship is suggested. The long Mindel-Riss interglacial coincides with the British major glaciation, while the Riss glaciation appears to be related in time to the 100-ft. beach submergence. There is, however, one striking anomaly ; the Mindel glaciation appears as an obvious misfit. When the trend of opinion among Continental workers (4) is considered, the difficulty disappears. That opinion leans either to eliminating or diminishing the extent of the Günz glaciation, while strongly emphasizing the importance of the Mindel-Riss interglacial period. An emendation of Penck's curve thus being called for, the Günz glaciation will be reduced to half its original duration, and a recession of the ice substituted for the Günz-Mindel interglacial. This serves to extend the duration of the Mindel-Riss interglacial. The result of the emendation is to emphasize, what was already sufficiently definite, the coincidence in time of the Alpine Mindel-Riss interglacial period with the British major glaciation.

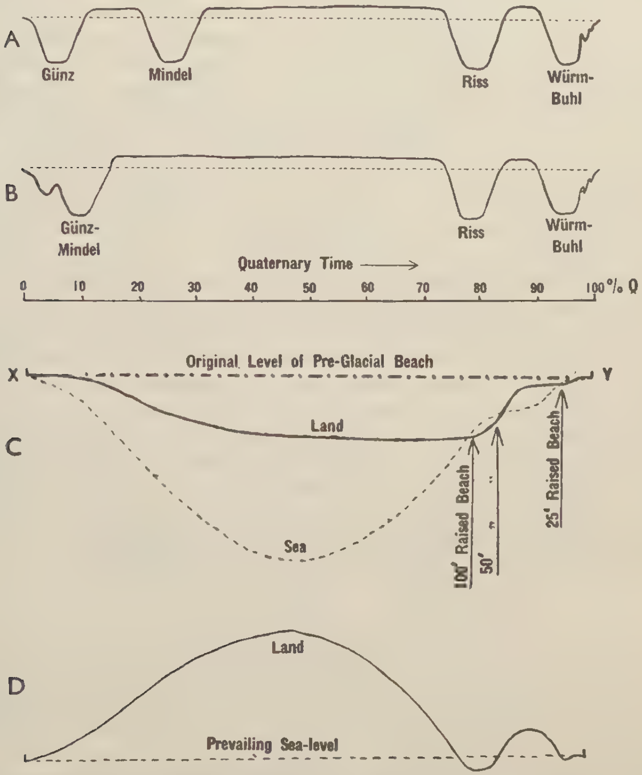


FIG. 1.—A. Penck's original Climate Curve for the Alps. B. Penck's Climate Curve emended after Solch. C. The new British Raised Beach Graph. D. The Derived Land Elevation Curve.

It now remains to discuss the accuracy of the dating of the beginning of the submergence recorded by the 100-ft. beach in the raised beach curve. The estimates adopted for the isostatic depression of the land and for the lowering of the sea-level are open to correction when better values are available. The effect of varying either of these estimates will be to alter the position on the time scale of the critical first intersection of the land and sea curves. The isostatic depression is almost certainly too low an estimate; any correction would bring the critical point earlier in time. The sea depression curve may, eventually, have to be lowered in the direction of Brögger's value of 2,600 metres; this would shift the point to a slightly later date. There still remains another source of uncertainty to notice. The sea depression curve is based on the pendulum-swing nature of the vertical oscillation with a slight displacement to the left to account for the abstraction of ocean water to form the land ice. This was the only course open in the absence of knowledge as to the cause of the sea depression that forms our postulate. From a consideration of possible causes it seems probable that any correction called for would be in the direction of shifting the lowest point of the curve to the left and thus bringing the critical first intersection point earlier in date. Varying the horizontal scale by increasing the length of $X-Y$ brings the date of the first intersection later while Penck's curve retains its time relations on the new scale. Before, however, the increase in length can impair the suggested relationship of the Riss glaciation and the Yoldia Sea the percentage of Quaternary time left would be inadequate to accommodate the important events that must be crowded into it. The tendency of these corrections is to cancel each other, and on balance of probability it seems justifiable to consider the date of the beginning of the 100-ft. submergence as a reasonably good first approximation.

IV. Scope of Inquiry Extended.

The inquiry could not be left at the stage where the comparison of the two curves had revealed such unexpected coincidences. It pointed to the probable existence of a chain of events in which the raised beaches of Britain and the three glaciations of the Alps were distant but related links. An extension of the scope of the inquiry, therefore, became necessary. Few, if any, workers in glacial geology would question the view that the major glaciations of the British Isles and Scandinavia were substantially contemporaneous, and that the 100-ft. raised beach is a record of the Yoldia sea submergence. In what follows they will be referred to as the northern ice-field and the Yoldia sea submergence. It is now possible to devise a new diagram, Fig. 2, and trace the influence of the glacial anticyclone which the northern ice generated. The curves in the new graph must of necessity be a little complex in nature, for it is necessary to depict the variations in the intensity of the anticyclone as the ice field waxed and waned and re-advanced before at last shrinking back to its present limits; Penck's Alpine climate curve must find an appropriate place and means must also be found for tracing the direction of the displacement of the Atlantic storm track in its migrations under the influence of the anticyclone.

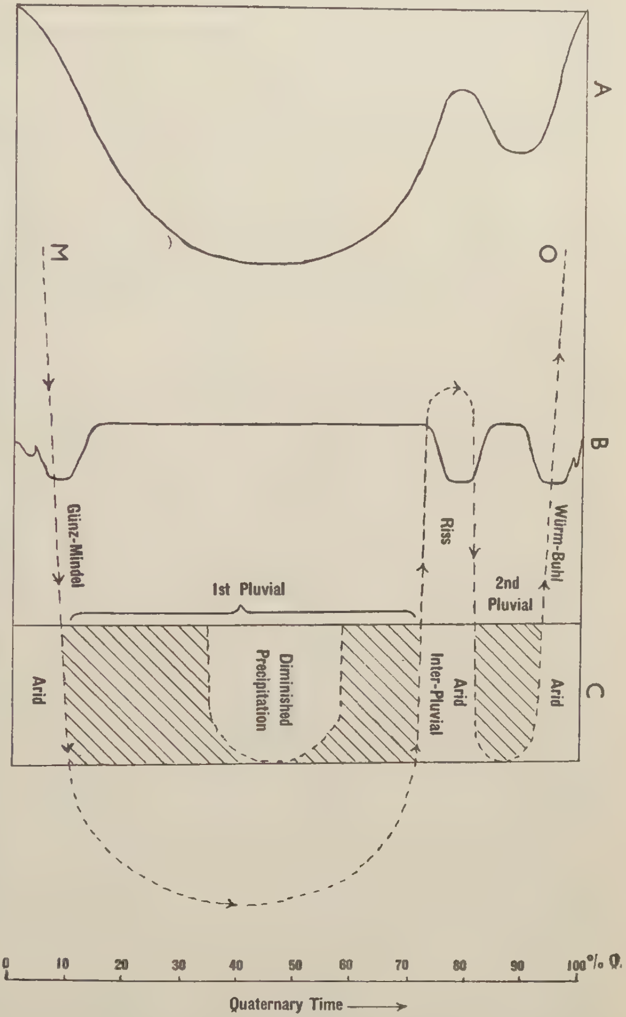


FIG. 2.—A. Intensity Curve of the Northern Glacial Anticyclone. B. The Alpine Climate Curve of Penck (emended). C. The Pluviated Region. M–O. Displacement Curve of Atlantic Storm Track. X–Y. Quaternary Time Scale.

The Atlantic cyclonic moisture-laden track normally runs across Britain and up the Baltic, and must have suffered a varying amount of displacement during the northern glaciation. In Fig. 2 all these episodes appear as an ascending series, each with its own time intervals, and all drawn to the same time scale. The axis of the Atlantic storm belt always remains at right angles to the graph. The direction in which it is displaced is indicated by the rather complicated dotted curve M–O. This curve commences at M early in Quaternary time, doubles back upon itself in Riss time for a return visit as far as the Alps, and completes its course at O, the same geographical point, but now at the close of the Quaternary cycle and therefore near the top of the graph. As it was also found necessary to provide a pluviated region to accommodate the storm track at the periods of maximum displacement, it meant that the graph represented, in the simplest form found practicable, no less than five variables. It, however, acquired the merit of depicting in one picture the Quaternary climatic changes as a whole over an extensive region, with each link in the chain of events in its proper place.

The nature of these changes and their relation as cause and effect will now be described. At an early stage in the development of the northern ice-field the anticyclone it generated would be just strong enough to push the track of the Atlantic storm belt slowly southwards over the Alps, there causing the growth of the Günz-Mindel glaciers during its passage. As the anticyclone gathered strength the storm track would move further south to leave the Mindel glaciers to dwindle and shrink back for want of nourishment. The elevation of the Alpine region during the first of its glaciations was sufficient to reduce its mean temperature to the point where glaciers could extend when there was increased precipitation. But even increased elevation and lower mean temperature could not preserve the glaciers when the rain-bearing winds had been pushed far to the south, and the glacial anticyclone had extended its influence. The Atlantic storm track now lay over some region south, and maybe reached east, of the Mediterranean sea. The area marked pluvial region now receives the precipitation it brings. Equilibrium is not achieved, for the northern ice-sheet is reaching the limit of its extent, and the anticyclone its maximum intensity, with the result that the storm track is displaced to the south of the pluviated area. The weakening of the anticyclone as the northern ice-field diminishes in extent enables the storm track to re-occupy the pluviated area and then in Yoldia sea time to move north as far as the Alps, there to leave its record in the Riss glaciation. But this visit differs from the mere passage of the Alps recorded in the Günz-Mindel glaciation in that the storm track only reaches the Alps to double back south as the northern ice-field, by re-advancing, re-invigorates the anticyclone. This time the storm track occupies the pluviated region for a shorter period and does not extend its influence further south. The northern ice-field finally retreats and the anticyclone diminishes in force. The storm track makes its way back, crosses the Alps to cause the Würm-Buhl glaciation and ends its migrationary period by returning, near the end of the Quaternary time, to its normal position across Britain and up the Baltic. It left records of its complicated movements in important deposits in the pluviated region and in the Alps, which can now be dated with some degree of accuracy. Throughout all these climatic changes the Yoldia sea submergence occupies the key position. The 100-ft. beach of Britain, the Yoldia sea submergence of Scandinavia, the Riss glaciation of the Alps and the arid interpluvial period of the pluviated region appear as links in the Quaternary chain of events.

V. Climatic Considerations.

The extension of the scope of the inquiry has enabled a graph to be constructed that exhibits in broad outline the relation in time of striking climatic changes over a region that ranges from the northern ice-field with its tundra boundary to the warm South Mediterranean lands with the Alps standing midway. We can view the climatic pulsations as a whole and discuss their effect in detail in each of our three areas. The northern ice-field appears as the dominating influence with the anticyclone it generated as the active agent. The elevation of the land above the level of the ocean at any selected point in Quaternary time seems competent to determine the extent of the ice-field and explain its variations. The anticyclone would gain or lose in intensity as the ice-field waxed and waned. The Yoldia sea submergence interrupted what otherwise would have appeared in the north as one glaciation. The Alpine glaciations appear as secondary effects. The Alps stood high enough above sea-level on each occasion to render growth of the glaciers possible when visited by the migrating Atlantic storm track. The Günz-Mindel glaciation is the only one whose growth coincided with that of the northern ice-field. The Riss glaciation occurred when the northern ice-field had been reduced by the Yoldia sea submergence; the Würm-Buhl glaciation occurred during the final retreat of the northern ice. When the northern ice-field reached its two maxima the glacial anticyclone controlled meteorological conditions in the Alps where the glaciers had retreated into the recesses of the mountains. The climate prevailing would be the steppe conditions of Russia or Siberia, a loess period with long cold winters and short hot summers and scanty precipitation. The conditions that favoured glaciation having been discussed, it is only necessary to trace the changes that the Riss-Würm interglacial period underwent to show that the climatic problem is rather complex. Accepting, for the moment, the relationship of the Yoldia sea submergence to the Riss glaciation exhibited in Fig. 1 as representing the facts, we find that the Riss glaciers retreated to be succeeded by a warmer interval with oceanic climate, until the rise of the land and the re-advance of the northern ice displaced the moisture-bearing Atlantic winds towards the south and brought on steppe conditions with loess formation. Neither glacial nor interglacial Alpine periods lend themselves to simple definitions. Though the South Mediterranean land has been suggested as the area occupied by the Atlantic storm track during its two periods of displacement to south of the Alps it is not intended to discuss African pluvial periods further than to point out that the time relations of the two pluvial periods shown in Fig. 2 were determined by the migrations of the storm belt. They are a consequence of the fluctuations in intensity of the northern glacial anticyclone. They are definitely dated as contemporaneous with the two Alpine interglacials.

One factor in the Quaternary history of the Alps has been omitted. Each glaciation will have been accompanied by isostatic depression, from which recovery would take place during each of the two interglacials. These oscillations of absolute land level must be represented among the raised beaches of the northern Mediterranean coast lands. Uncertainty as to their relations must be the excuse for omitting their consideration from this paper. There remains one feature of the Alpine glaciations which might possess significance. The Günz-Mindel glaciation, as it appears in the emended climate curve of Penck, is the mirror image of the Würm-Buhl glaciation. The Atlantic storm belt approached the Alps from the north when the first of these glaciations occurred and from the south when the last was recorded. The storm belt is cyclonic in character ; the connection, if any, must be left for the consideration of the meteorologists.

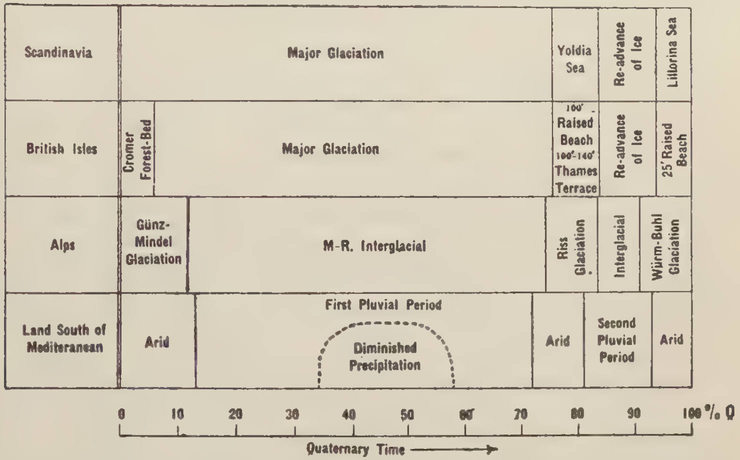
VI. Correlations.

An investigation which originated in an attempt to determine the nature of the British strand-line oscillations has led far afield as cause, effect, and consequence were followed. The results obtained not only suggest unexpected correlations, but make it clear that the Quaternary geographical and climatic cycle must be treated as a whole. Results obtained for a limited area only reveal their full meaning when their relationship to adjoining areas has been elucidated. A summary of the correlations that emerged in the course of the investigation are tabulated in the correlation table. The length of each time interval has been taken from the relevant graph. It serves to state the conclusions reached in the form that best invites criticism and a rigorous test of their validity.

That the table will require corrections in detail is possible, but its principal feature, that the Alpine Mindel-Riss interglacial period was contemporaneous with the major glaciation of Scandinavia and the British Isles, seems to be definitely determined. The glacial sequences of the Alps and Scandinavia thus appear in the unexpected relation of positive and negative.

It will be noticed that the 100–140-ft. Thames terrace has been placed in the Yoldia sea period. It is only necessary to consider the necessity for drainage of the ice front along the northern banks of the Thames in pre-Yoldia sea times to recognize that the submergence must have drowned an existing valley. The land along the margin of the ice would be frozen hard during the long winter, but summer heat would cause rapid thawing and considerable flooding. It is not suggested that the 100-ft. raised beach and the 100-ft. Thames terrace were strictly contemporaneous. The Yoldia Sea period was a long one with land and sea rising at rates that varied from time to time and from place to place. In it there is room to place the raised beaches, the Thames terrace, the Kirmington fossiliferous beds, and any other deposits that record the submergence in the order of their date when that can be determined.

QUATERNARY CORRELATION TABLE.



VII. CONCLUSION.

The Quaternary Ocean Depression hypothesis has provided what appears to be a rational explanation of that great cycle of events which included striking climatic changes and important variations in the distribution of land and sea. It has enabled the course of these changes to be depicted graphically so that they can be viewed as a whole and yet considered in detail at each step in their development. Together with the correlation table, the graphs provide ample scope for the application of a rigorous critical test. But even proved ability to explain the facts in the restricted region dealt with would not, alone, suffice to invest the hypothesis with the status of a theory.

It rests on its first and only postulate that the sea suffered during Quaternary time a temporary depression of its surface level of 1,000 metres or more, from which it recovered. Such a change of ocean level must be world wide in extent, simultaneous everywhere and equal in magnitude and rate of change. It must have important consequences, and it should be possible to recognize its effects in widely distant regions.

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Subsidence in the European Area.

By R. G. Lewis.

THE structure of the earth was supposed by Suess to be tripartite, there was an outer layer of rocks mainly granitic, the sal, or sial as it is usually now called. This rested, or " floated ", on a dense layer called the sima, of basaltic character, within which was the earth's core, or nife, metallic in nature. Such a simple conception has been modified in the light of later knowledge: geologically there is much evidence pointing to the existence of several shells of increasing density within the crust. This is to some extent supported by the evidence of seismology, the layers below the upper sedimentary layer being the Granitic, the Intermediate (of tachylyte or diorite) and Lower Layers (dunite, peridotite, or eclogite) (1).[1] According to the latest information there are four layers intermediate between the granitic and lower layers: the thickness of the sedimentary layer varies from about 2 to 6 kilometres in mountainous regions: the thickness of the granitic layer varies, being about 10 to 12 kilometres in Central Europe. In low-lying regions the total thickness of these two layers is probably about 6 kilometres less than in mountainous regions: " the thicknesses of the other layers are very difficult to determine; the upper two probably have together a thickness of about 15 kilometres, but the others can hardly be determined from the observations " (2).

Joly, following Strutt (Lord Rayleigh), contended that all the heat which is escaping from the surface of the earth can be more than supplied by the radioactivity of the sial rocks, and showed that, if these have an average thickness of 30 kilometres, the temperature at their base must be about 1,050° C., or nearly the melting-point of basalt (1,150° C.). He calculated that eventually sufficient heat would accumulate to reduce the layer to a molten condition, and went on to consider the interesting changes which would then take place on the earth's surface (3). For the purposes of the present paper it is not necessary to go into Joly's speculations further : it is sufficient to note that a layer may by the accumulation of heat due to radioactivity reach a plastic, or even a molten, state. Without doing violence to the argument it may also be assumed that such a state would be reached sooner under a continent, the greater thickness of sedimentary rocks here acting as a blanket in reducing the rate of heat-flow to the outer air, than under the sea ; that is, the ocean as distinct from an epicontinental sea.

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[1] See Notes and References at end.

The great mass of information collected by the Terraces Commission of the Union Géographique Internationale (4), when digested, provides a means of appreciating the behaviour of parts of the earth's crust during the time—spread over probably some of the Tertiary and most of the Quaternary—when the raised beaches, the subject of their investigation, were being formed. The writer drew attention to the difference in behaviour between certain sites and others, and drew the conclusion that a layer of the earth's crust was discontinuously in a molten or plastic condition. This conclusion was strengthened and extended to the deduction of flow in such a plastic layer (5).

The conception of such a process of forced flow is a simple one : there is no need for the suggestion—as with Joly—that a large area of the crust should become plastic at the one time. It is supposed that beneath a certain area the layer becomes plastic more quickly than is the case with those regions immediately adjacent, though they are nearly at the requisite temperature : the superincumbent mass commences to squeeze out the plastic material, which as an anticline of a plan determined by the plan of the mass, moves away from the latter in every direction, its temperature being maintained and increased by friction, so that the nearly plastic material immediately adjacent is at once reduced to plasticity and incorporated in the moving anticline.

The surprising flexibility of the sedimentary layer may be studied as a result of the discoveries of the Wegener Expedition to Greenland. This country has often been compared to a soup-plate full of ice, and one of the objects of the expedition was to sound the depth of the ice, employing seismological methods. The coast range, which corresponds to the rim of the soup-plate, rises on the west side to nearly 5,000 feet. It is necessary to descend on the inside of the range to reach the ice, which itself rises gently. The expedition established a camp at a point midway between the coasts and named this camp Eismitte : its height above sea-level was 9,000 feet. The thickness of the ice was here found to be 8,000 feet, and the bottom sloped up towards the coast range. Furthermore, leading coastwards the soundings disclosed what were described as fjords (6).

Such a physiographical appearance is that of a centrally disposed mountain range which has collapsed, squeezing a substratum out east and west and raising the coastal regions. This may, of course, be regarded as an isostatic movement—the weight of ice pressing down the crust at the centre—but this explanation could hardly hold at the commencement of the movement when the centre was high and the ice could escape freely seawards. The point is not, perhaps, important at the moment, since the required illustration is one of the crust's flexibility. At any rate, not only Greenland is affected, for the Fifth Thule Expedition, which operated more to the west, noted much recent raising of the land, with raised beaches a prominent feature of the coasts. Baffin Land has risen more at the south end than at the north. A typical extract is as follows: "Usugarsuk. It is a remarkable feature that now one cannot drive a sledge from the sea to the houses without having to pass over a number of naked stony shore ridges. . . . To build houses on this spot which is so difficult of access with a sledge would be quite absurd, especially as there are just as good sites on the lower shore ridge. Again we have evidence that the land must have risen considerably since these houses were built" (7).

As to Newfoundland, the southern coast has sunk while the country has been raised to the amount of 500 feet at the northern end of the island (8).

It may well be that these movements to the west and south of Greenland are connected with the collapse of the whole region accompanied by the squeezing out of a soft substratum. The recent earthquake in the Baffin Bay area taken with other evidence of vulcanicity referred to at the end of this paper is significant.

To come now to the European area: as far as the English Channel is concerned, it would appear that it is, in its present form, a recent feature. Chaput has placed it on record that all the French coast from Belgium round to the Pyrenees has been slowly sinking since a time which seems to connect with the later glacial period. The deposit underlying the recent alluvium is now at -20 to -30 metres. Change in the direction of flow of watercourses is additional corroboration (9).

On the English side of the Channel, Gilbert concludes that the Pleistocene raised beaches have "been almost entirely eroded during the widening of the English Channel" and draws attention to a submerged terrace at the 10-fathom (60 feet) level which can be traced on the Nautical Chart in horizontal lines for very long distances on both sides of the Channel (10).

A similar subsidence of the North Sea bed with widening of the southern end of the North Sea is to be inferred (11). The presence of a Maglemose culture at Holderness in Yorkshire has been taken to indicate that there was in those late times at least a temporary land bridge across the southern North Sea (12). The latest phase of the widening was the period from the eleventh to the thirteenth centuries A.D., during which islands disappeared and the Zuider Zee was flooded.

Munro (13) quotes a French writer who refers to a manuscript of the eighth or ninth century preserved in the library of Avranches in which it is stated that formerly there was, in the vicinity of Mont St. Michel, a dense forest extending six miles from the sea which harboured all manner of wild beasts. To show how much the sea has encroached on the land in these parts, the same writer—M. de Closmadeuc — reproduces a map of Contentin of the thirteenth century, which shows Mont St. Michel a long way inland, the island of Jersey as united to the Continent, and a corresponding increase of land all along the adjacent shores.

In other parts the memory of former land areas is enshrined in legends such as those of Lyonesse off Cornwall and St. Brandan's Isle to the west of Ireland.

Further south there is evidence of subsidence around the Iberian Peninsula. A submerged canyon definitely continues the direction of the present River Adour. " Near the present embouchure the channel is about 175 fathoms deep, or 117 fathoms below the platform in which it is cut. Further seawards it becomes a true rock-canyon 4,000 to 6,000 feet deep and, finally, it opens out at the foot of the continental slope at some 9,000 feet below present sea-level. The south side of the canyon is ravined, as if by tributary streams . . . similar phenomena are traceable off the following rivers : Gironde, Arosa, Lima, Douro, Carreira, Mondego, Tagus, and the English Channel River " (14).

E. Hernandez-Pacheco has shown (15) that the north of Spain has subsided. This seems to have occurred previous to the beach-forming period, as a set of terraces are present at the Bilbao site in correct position in relation to present sea-level. At the end of the beach-forming period, however, the peculiar movements of France in relation to those of Spain seem to show that subsidence of the bed of the Bay of Biscay was still going on in the vicinity of the French coast (5).

Further south still, the Canaries have subsided since the beach-forming period. Rovereto, in his survey (16), on the strength of Strombus Bubonius in the 7-m. beach, correlates this with Depéret's Tyrrhenian terrace at 55–60 metres, though Strombus would seem to be more characteristic of the Milazzian terrace at 35 metres. With whichever beach the correlation may be established, subsidence since that period may be assumed.

Up to this point, attention has been confined to a steady subsidence of the west coasts of Europe, no longer to be thought of as a number of local subsidences, but as part of a general scheme connected with the collapse of the bed of the Atlantic Ocean. It is now to be considered what part is played by the more stable areas of a continent attacked in this way. The attacking force would appear to be, as stated above, a moving anticline of molten material at a very high temperature urged onwards by the collapse of the upper layers of crust behind it, which progresses more or less horizontally through the crust in an almost irresistible manner. So far as its effect on the coastline is concerned, a picture of this effect can be produced if on a map the blue coloration of the ocean is imagined to be an acid slowly eating away at the coastline. Stable areas are then to be imagined as drawn in acid-proof ink round which corrosion proceeds, converting them first into peninsulas and then islands. Some such refractory property must reside in these stable masses whereby, either through more rapid conduction of heat to the surface or through an absence of the flux necessary for their fusion at these temperatures, they are little affected while the anticline eats its way round their bases.

Thus we see first Scotland and then England outflanked on the north and attacked from the rear, so that South-East England is now subsiding from the north-west south-easterly and not in accordance with the general line sloping from Central Europe to mid-Atlantic.

It will be remembered that the previous subsidence which ushered in the Cretaceous period left the West of England, Scotland, Brittany, West Spain and Portugal, and so on, unsubmerged.

As to the Mediterranean, a good regional study is that of the islands of the Dodecanese by Ardito Desio (17). During the Miocene and a large part of the Pliocene periods all, or at least the great majority, of the islands of the Dodecanese were united and formed part of Asia Minor (p. 46). A long cycle of erosion had cut down the mountains and filled lakes and valleys with alluvium. Even the climate was affected, becoming drier, and here and there desert conditions prevailed. A diastrophic period now commenced which produced a slight folding of the neogenic sediments and especially vast alterations in land level. The continent was dismembered and irregularly submerged ; there only remained on the surface of the sea a portion of the highest reliefs, forming an archipelago (p. 47). The upper of the beaches which began to be formed are dated on paleontological evidence to the Lower Quaternary, and the lower beaches to the Upper Quaternary (p. 45). He scouts the idea of a sinking of sea-level and concludes for an irregular uplift of the land during the Quaternary (p. 45). Warping of the terraces in places points to subsidence since the beach-forming period. Marinelli called this the " prehistoric subsidence ". This movement is very recent, and, if it commenced in prehistoric times, it continued into historic times (p. 45). Desio goes on to say, " This phenomenon of subsidence seems fairly general, not only in the Aegean, but in the whole Mediterranean. This does not mean to say, however, that in some places indications of recent emersion are lacking," and quotes the case of a recent beach a few metres above the sea on the island of Cos (p. 45).

Before discussing the above, it will be as well to consider the evidence in Greece on the opposite side of the Cyclades, where terraces are present in embarrassing profusion (18). Negris first mentions those of Mount Voïlias, which are compared in Fig. 1 with those at Bilbao. In this figure, for purposes of comparison, both sets were made to commence at the same height of 40 metres, to which end 910 metres were deducted from the Mount Voïlias heights. It is interesting that the conclusions of Negris include (p. 25) an alteration of base-level from about 900 metres to zero. The author remarks that the great height of the terraces need cause no astonishment if it is recalled that the Pliocene formations of the Gulf of Corinth have been raised to 1,759 metres (p. 19). His third category of terraces is most interesting. He says, " If from Cape St. Nicholas, the western point of Mount Geraneia, one looks across to the coast of the Peloponnesus, these terraces are seen to melt into a single surface, inclined to the sea " (p. 19).

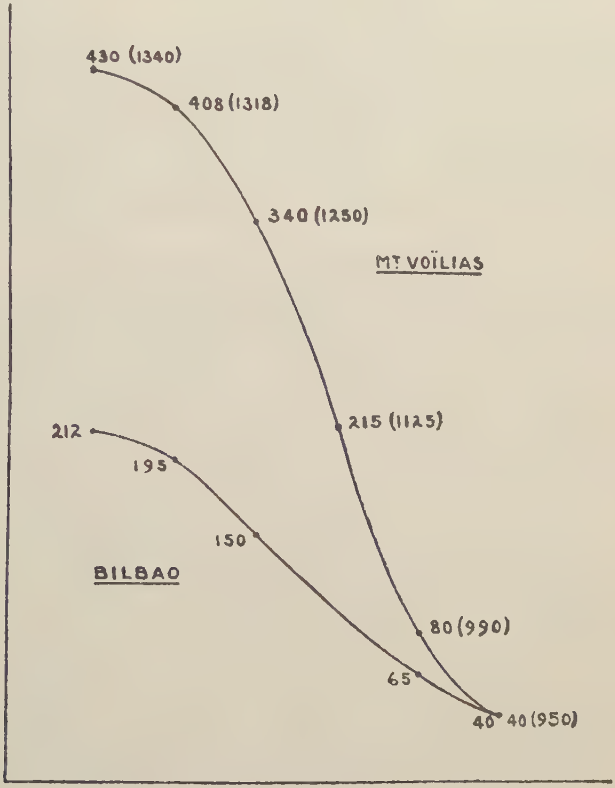

FIG. 1.

Here we have a record of the spasmodic manner in which the elevation farther east was carried out : the terraces are to be regarded as one, split up by a tectonic movement hinging about the point at which they join. Similar, though smaller, spasmodic rises are to be suspected in other parts of Greece, judging from the great number of terraces and other traces of sea-level, differing in height from one another by a few metres. Sets of terraces in this category are found in Baffin Land (7) and the Argentine (19), to mention only two quarters.

Negris mentions that the Southern Peloponnesus has subsided though the north has risen (p. 22).

In general, the movements in Greece can be summarized roughly as elevation into a dome at the Gulf of Corinth ; but much of the region under review stands higher than might be expected. In the Cyclades, Negris mentions lithophagus perforations at 690 metres, whereas the highest beach at Mount Voïlias, after deduction of 910 metres (as in Fig. 1) for elevation since the beach-forming period, stands at 430 metres. This goes to show that in the Western Cyclades the elevation since the beach-forming period is 690 — 430 = 260 metres.

The course of events in the Aegean would therefore seem to have included the subsidence of a land area embracing at least the Dodecanese and the Cyclades, the subsidence being at a maximum in the Lower Quaternary, so that there only remained on the surface of the sea a portion of the highest reliefs. This was also the commencement of the beach-forming period and, as there is occasional evidence for a rise of land between each two subsidences, during this period large areas of the Aegean would be intermittently dry land. Anticlines of plastic material squeezed from areas on all sides of the Peloponnesus met under the Gulf of Corinth region and raised the land steadily during the beach-forming period and since. Traces of a recent beach in the Dodecanese and elsewhere seem to mean that there may be a present rise affecting these regions, and this may be due to the subsidence of the Mediterranean bed south of Crete, which is itself slightly raised, as the sea is now farther from the palace at Knossos than when that palace was built.

The possibility of the existence of a large Cycladic island at a comparatively late date is especially interesting to prehistorians in view of the difficulty of pointing with certainty to the region where neolithic culture first developed or to the region whence came the earliest Chaldean and Egyptian civilizations.

Data in regard to the Palestine coast are scarce. Near Gaza Petrie gives evidence for a submersion of about 125 feet (20). The general conclusion reached for the Egyptian area (apart from the Nile Valley) is that there are no raised beaches or terraces in the areas adjoining the Mediterranean coast ; but that depression seems to have been more marked than elevation for at least two thousand years (21).

This rapid survey of the Eastern Mediterranean leads to the conclusion that a large general subsidence commenced before and has continued after the beach-forming period.

It may at first sight seem strange to adduce evidence of local uplift as an argument for subsidence ; but it may be pointed out that the subsiding area is large and those areas which have been raised are small in proportion. Also, according to this theory of Plastic Flow, the first effect of subsidence is a raising of the marginal areas which is later followed by their slow and complete submersion (5).

In Italy, which helps to divide the eastern from the western basin of the Mediterranean, tectonic movements are continuing ; but in general the coasts are subsiding (22). On the lines of the kind of action that has, above, been stated to have resulted in the present topography of the Aegean, it is to be supposed that the raising of the Appenines has resulted from the subsidence of the bed of the Adriatic on the one hand and of the Tyrrhenian and Ligurian Seas on the other. Sardinia, one of the last remnants of Termier's Corso-Sardinian land-mass, has subsided considerably, the Tyrrhenian beach of Depéret being now at only 1–10 metres.

A comparison may be made between the appearance of Greenland, mentioned above, and this region, which is the same thing on a smaller scale. The Adriatic would represent the subsiding centre of Greenland which has caused a ridge to rise each side of it in the Appenines and Dinaric Alps : Sicily takes the place of Newfoundland, the north coast being raised to a great height.

A long and exhaustive survey of the peneplaned surfaces and terraces of Italy and Sicily is given by Gortani (23). The marine terraces of Italy, equally with those of Greece, seem to have been formed during spasmodic emergence.

Coming to the extreme Western Mediterranean, the Gulf of Lyons coast would appear to be one of slow subsidence with which alluvium has kept pace, as in the north and west of France (9). But as to South Spain, only the Gulf of Valencia coast seems to have subsided, there being Pliocene and Pleistocene deposits elsewhere (15).

To account for the spread of palaeolithic cultures, prehistorians long ago found it necessary to assume intermittent land connection between Africa and Europe, and it has been usual to suppose that such land bridges crossed at the Strait of Gibraltar and between Tunis and Sicily ; but the archaeological succession in France and in Spain does not encourage the view that many cultures arrived in France by way of south Spain or of Italy. If at any future time proof can be brought forward of the existence of a large prehistoric island having intermittent connection with France on the one hand and Tunis on the other, such proof would be welcomed by many as the solution of a difficulty. In this connection it may be mentioned that Gordon Childe (12) records a strong Western Mediterranean influence, in some respects analogous to that of the Cyclades, the source of which has not been located, contemporary with the earlier Minoan periods.

The Mediterranean as we know it to-day is, then, the result of a number of local subsidences, none of which can be said to be completed, which have converted it from two small lakes into an epicontinental sea.

Up to this point no mention has been made of vulcanicity ; but it can be appreciated that no subsidence working through the fusing of the foundations of adjoining regions could be imagined unaccompanied by some manifestations of vulcanicity. Earthquakes and tidal waves during spasmodic settling or rising of the upper crust leave little trace discoverable after the passage of time ; but there are other more lasting traces in the lava flows from volcanic vents.

" Vulcanicity (in south Spain) commenced to manifest itself during the Miocene, underwent great development during the Pliocene and continued to be active after that period " (15). In Central France vulcanicity seems to have continued late, as a human jawbone embedded in lava has been discovered. Both these regions are now dead except for a few hot springs. Activity still continues in the Central and Eastern Mediterranean.

A different proof of the progressional nature of vulcanicity is afforded by the alteration in the character of the lava from one vent : if subsidence is effected by the squeezing away of successive layers of the substratum, lavas should show a definite succession—the layers nearest the top contributing the acid and those lower down the basic lavas. Such a succession can in fact be seen in process at Etna, where the lavas from the old axis of Trifoglietto were andesites, but those rising in the present conduit are basaltic (24). In the north of Patagonia the andesites are of Miocene age and covered by Pliocene basalts (25). In the Berkeley Hills near San Francisco there is a repeated succession of rhyolites, andesites, and basalts (26) which seems to witness to more than one subsidence.

The subsidence of the Mediterranean has been going on side by side with that of the west coasts of Europe and, as the latter should be thought of as part of a general scheme connected with the collapse of the bed of the Atlantic Ocean, so the former should be thought of as connected with the general subsidence of Europe. According to the present theory, some such curve would mark the limit of the general subsidence as the following dry belt : Qizil Qum–Qara Qum–Iraq–Arabia–Sinai–the Sudan and West Sahara to the Atlantic at Rio de Oro. Contained within this curve are the Caspian and Black Seas and Russia. The White Sea and the Volga Valley cut deeply into Russia, whose north coast has all the appearance of one of subsidence, though confirmation of this is lacking. In regard to the Black Sea (27) the following extract from the Russian geologists' report speaks for itself : " Conclusive data have been furnished by the sea-bottom investigations carried on off the shore of the Crimea. They have shown that the abrupt cliff separating the littoral shallow-water zone of the bottom from the central depression—which is some 200 metres deep—was produced by faulting: the latter had taken place in part at very recent date, posterior to the New Euxine epoch, i.e. in post-Glacial time. . . . There is, therefore, no doubt that the deep depression of the Black Sea is an enormous *graben* with an area gradually increasing due to the reiterated peripheral faulting. Furthermore, apart from the sinking dependent on the faulting, there occur other slow downward movements affecting the littoral shallow-water region. During the post-Glacial time a part of such shallow-water zone adjacent to the steep cliff has sunk for over 100 metres."

The writer wishes to express his indebtedness to Dr. K. S. Sandford and Professor Arthur Holmes for criticism (which has been deferred to) and several of the references.

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(17) *U.G.I.*, ii, 4.
(18) *U.G.I.*, i, 4.
(19) *U.G.I.*, ii, 16.
(20) *U.G.I.*, i, 2.
(21) *U.G.I.*, i, 1.
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(24) *Ency. Brit.*, 1929, "Volcano."
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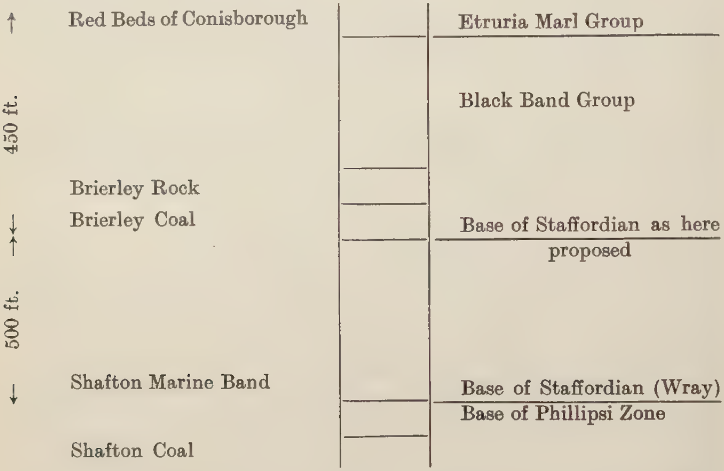
The Flora of the Upper Westphalian in Yorkshire.

By James Walton, B.Sc. (Lond.), Leeds University.

The base of the Phillipsi Zone, which Professor Trueman has made the base of his Upper Westphalian, is taken at the horizon of the Shafton Marine Band in Yorkshire (1)[1] and in consequence the following beds are included in this zone :—



In order to determine any floral breaks it was found necessary to examine the various assemblages commencing at the horizon of the Shafton Coal and working upwards to the beds at Conisborough.

The colliery at Brierley was chosen as a suitable collecting ground for the Shafton Coal, because the sandstone and shale forming the roof yield a prolific flora, and the plants obtained were :—

	Radstockian.	*Staffordian.*	*Yorkian.*	*Lanarkian.*
Lycopodiales.				
Sigillaria scutellata Brongt.	0	2	8	3
Bothrodendron minutifolium (Boulay)	0	1	6	1
Sigillaria sp.				
Lepidodendron sp.				
Cordaitales.				
Artisia transversa Artis .				
Equisetales.				
Calamites sp.				
Pteridospermae and Filicales.				
Neuropteris heterophylla Brongt.	1	2	10	4

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[1] Numbers in parentheses refer to the list of references at the end of the paper.

	Radstockian.	*Staffordian.*	*Yorkian.*	*Lanarkian.*
Neuropteris tenuifolia (Schloth.)	0	6	10	0
Neuropteris rarinervis Bunbury	9	8	3	0
Neuropteris gigantea Sternb.	0	3	10	3
Alethopteris lonchitica (Schloth.)	0	1	10	4
Mariopteris muricata (Schloth.)				
Gymnospermous Seeds.				
Trigonocarpus parkinsoni Brongt.				
Sphenophyllales.				
Sphenophyllum cuneifolium (Sternb.)	0	1	10	3

The figures in the right-hand columns express the relative frequencies of the species in the various series as determined by Dr. Crookall (1–2 = very rare; 3–4 = fairly rare; 6–7 = fairly common; 8–10 = very common) (2). From these it will be seen that the flora associated with the Shafton Coal is quite definitely Yorkian, the chief diagnostic species being *Bothrodendron minutifolium*, *Neuropteris heterophylla*, *Alethopteris lonchitica* and *Sphenophyllum cuneifolium*. *Neuropteris rarinervis* Bunbury is the only Staffordian species present, and this has been found, though rarely, on Yorkian horizons in other coalfields.

At the horizon of the Brierley Rock there is a marked change in the flora and the following plants were collected from the shales underlying the Brierley Rock at Hemsworth :—

	Radstockian.	*Staffordian.*	*Yorkian.*	*Lanarkian.*
Lycopodiales.				
Lepidodendron sp.				
Sphenophyllales.				
Sphenophyllum majus (Bronn.)	1	3	4	0
Cordaitales.				
Cordaites sp.				
Pteridospermae and Filicales.				
Neuropteris pseudogigantea Potonié	0	3	10	3
Linopteris obliqua (Bunbury)	0	8	2	0
Neuropteris tenuifolia (Schloth.)	0	6	10	0

Linopteris obliqua and *Sphenophyllum majus* are Staffordian plants and the Brierley Rock must be referred to the Staffordian stage. *Neuropteris tenuifolia* and *Neuropteris pseudogigantea* occur on both Staffordian and Upper Yorkian horizons and are not, therefore, of themselves diagnostic as between the two divisions.

Little work has been done on the floras associated with the uppermost Coal Measures in Yorkshire, so that the section at the Ashfield Brickworks, Conisborough, merits more detailed consideration. The sequence is as follows :—

		Ft.	in.
Permian	Drift	8	0
	Oolites	12	0
	Red and Grey Marls	3	0
	Sandstone	5	0
Etruria Marl Group	Deep Red Mudstone	30	0
	Green and Yellow Shales and Mudstones	3	6
	Pale Green Sandstone	10	0
	Dark Blue Shale	1	3
Black Band Group	Coal		2
	Bind	5	0
	White Fireclay	7	6
	Brown Fireclay	3	0
	Sandstone	12	0
	Grey Mudstone	1	0
	Coal		11
	Fireclay	12	0
	Grey Soapy Shale	18	0
	Shales with *Anthracomya phillipsi*	1	0

The beds here referred to as the Etruria Marl Group are the only beds in this quarry which yield any plants.

The Flora of the Etruria Marl Group in Yorkshire.

This is the only place in Yorkshire where plants can be collected from the Etruria Marl and, as a matter of fact, it is one of the few Yorkshire localities where the Etruria Marl Group is exposed. The following flora was obtained :—

	Radstockian.	*Staffordian.*	*Yorkian.*	*Lanarkian.*
Lycopodiales.				
Stigmaria ficoides (Sternb.)				
Cordaitales.				
Cordaites sp.				
Filicales and Pteridospermae.				
Neuropteris heterophylla Brongt.	1	2	10	4
Neuropteris rarinervis Bunbury.	9	8	3	0
Neuropteris gigantea Sternb.	0	3	10	3
Sphenopteris sp.				
Pecopteris sp.				
Renaultia rotundifolia (Andrae)				
Filicales and Pteridospermae incertae sedis.				
Cyclopteris reniformis Brongt.				

	Radstockian.	*Staffordian.*	*Yorkian.*	*Lanarkian.*
EQUISETALES.				
Annularia sphenophylloides (Zenker)	7	3	1	0
Annularia stellata (Schloth.)	10	3	1	0
Pinnularia columnaris (Artis)				
Pinnularia capillacea				
Calamites sp.				
Asterophyllites charaeformis (Sternb.)				

This admixture of Yorkian and Radstockian species can be ascribed to a Staffordian age. It is particularly fortunate that a good suite of fossils has been obtained from these beds, for the Etruria Marl Group of North Staffordshire yielded only *Neuropteris scheuchzeri* (3). From the Brick Clay Series (Old Hill Marls) of South Staffordshire, however, Arber obtained a rich flora which included practically all the diagnostic species which the writer has obtained from the Yorkshire beds, namely, *Neuropteris heterophylla*, *Neuropteris gigantea*, *Renaultia rotundifolia* and *Annularia sphenophylloides* (4).

The specimens of *Neuropteris heterophylla* Brongt. (Fig. 1*c*) are particularly well preserved and the fronds are often in an unflattened condition. The terminal pinnule is present in nearly every case. The fan-shaped leaflets embracing the main axes of the *Neuropteris* fronds and referred to as *Cyclopteris reniformis* Brongt. (Fig. 1*c*) are quite often found although they tend to break up rapidly. *Neuropteris gigantea* Sternb. and *Neuropteris rarinervis* Bunbury are rare.

Renaultia rotundifolia (Andrae) is occasionally obtained bearing sporangia along the margin of the pinnules. They usually occur singly but sometimes are arranged in groups of two or three. Arber recorded this plant from the Etruria Marl Group of Staffordshire as *Sphenopteris* (*Renaultia*) *Schwerini* (Stur), but Kidston, after examining the plant, placed it under *Renaultia rotundifolia* (5). The figures of Arber's plants are very similar to those collected at Conisborough (Fig. 1*e* and *f*).

The Equisetales are confined to indeterminable stems of *Calamites* sp., *Annularia sphenophylloides* (Zenker) and *Annularia stellata* (Schloth.). The leaves of *Annularia sphenophylloides* (Zenker) (Fig. 1*b*) are spoon-shaped and broaden from the base towards the apex, ending in a fairly blunt point. There is a general tendency towards the formation of elliptical whorls which usually touch each other. The individual leaves have a length of 5–9 mm., and a maximum width of 1–2·5 mm. and thirteen is the average number of leaves in a whorl. *Annularia stellata* (Schloth.) (Fig. 1*a*) has leaves having an average width of 2·5 mm. and an average length of 30 mm. The usual number of leaves composing a whorl is eighteen.

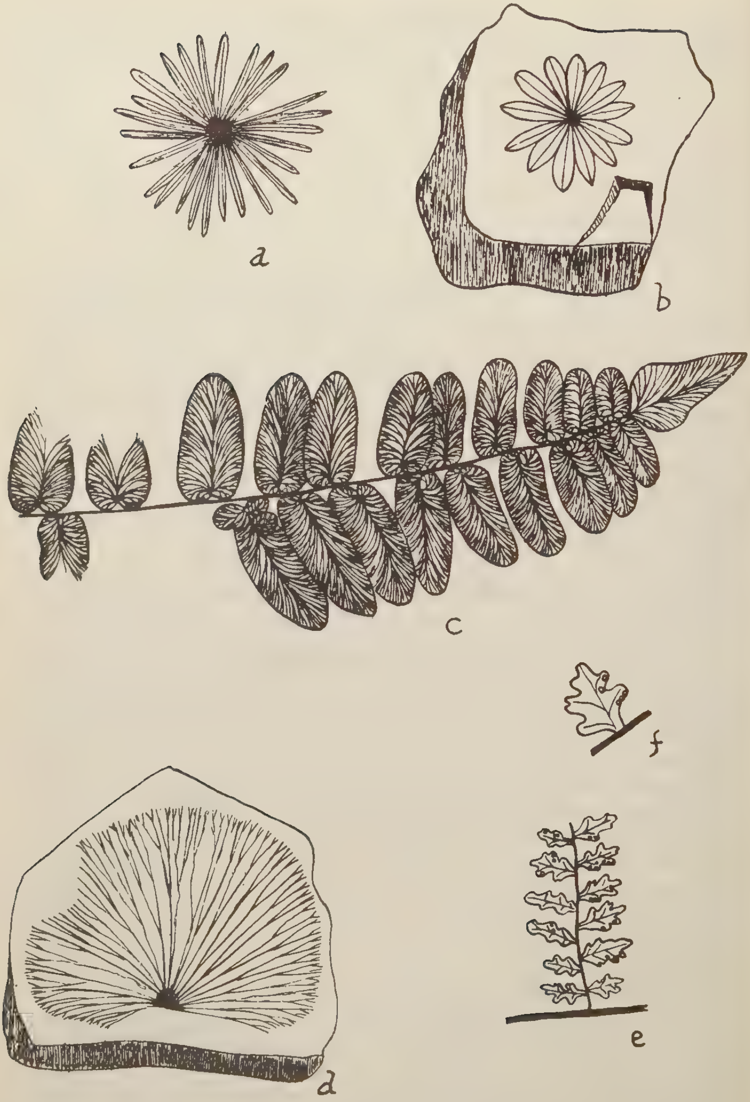

FIG. 1.—Typical Plants of the Etruria Marl Group of Yorkshire.

(*a*) Whorl of *Annularia stellata* (Schlotheim) × 1. Locality: Ashfield Brick pit, Conisborough.
(*b*) Whorl of *Annularia sphenophylloides* (Zenker) × 1. Locality: As for (*a*).
(*c*) Frond of *Neuropteris heterophylla* Brongniart × 1. Locality: As for (*a*).
(*d*) *Cyclopteris reniformis* Brongniart × 1. Locality: As for (*a*).
(*e*) Frond of *Renaultia rotundifolia* (Andrae) × 1. Locality: As for (*a*).
(*f*) Pinnule of *Renaultia rotundifolia* (Andrae) enlarged to show sporangia. × 2.

CONCLUSION.

In view of the above facts it seems desirable to draw the base of the Staffordian in Yorkshire at the Brierley Coal rather than at the Shafton Marine Band, as suggested by Dr. Wray (6). This is about 500 feet above the base of the Upper Westphalian of Trueman, although it coincides with the horizon at which definite forms of *Anthracomya phillipsi* are first met with (7).

Finally, I would like to express my best thanks to Dr. Crookall for his continued assistance and to Miss C. E. Armitage for her help in the collecting of plants.

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REVIEWS.

ÜBER WERDEN UND ZERFALL VON KONTINENTALSCHOLLEN. By AXEL BORN. Forts. d. Geol. u. Palaeont. Band X, Heft 32, pp. 347–422, with 10 maps. Berlin: Borntraeger, 1933.

THE main object of this book, as set forth in the first lines of the introduction, is to provide an account of the present state of knowledge as to the growth and structure of the existing continents. The author states his personal opinion that the time has not yet arrived for a general synthesis, since our knowledge of the continents other than Europe is not yet sufficiently complete, and in this attitude most unbiassed geologists will doubtless agree with him. A book written on these lines obviously does not lend itself readily to criticism, since it is for the most part a statement of known and agreed facts, as to which little difference of opinion can exist. It must be admitted that the author has rarely obtruded his own personal views: it is, however, clear that he is not enamoured of the Wegener theory. His views may perhaps fairly be summed up as strongly inclining to orthodoxy, especially when it takes the form of a successive enlargement of the continents by "zonary accretion" as it may conveniently be termed. It is possible, however, that some of his ideas as to what really constitutes a continent, or parts of one, may not commend themselves to some of the stricter disciples of the school of Suess, because in places it seems to be implied that what looks uncommonly like a geosynclinal may in reality be part of a continental block ; some of the arguments on this subject are a little difficult to follow. As a matter of fact, in a good many recent writings on this subject the widespread and increasing use of the conception of a shelf does not altogether tend to clarity.

On another point also, which is noted, though not very much stressed by the author, many geologists will feel some degree of sympathetic agreement ; namely, that the modern tendency to minute subdivision of the chief tectonic episodes into something like thirty in Palaeozoic and later times instead of the original three or four, has tended to obscure the whole matter, and to give the impression that orogeny is going on somewhere all the time (which is probably true). However, the theory of zonary accretion seems to presuppose something of the nature of earthwaves, and if this is so, it is obvious that such waves must take time to travel, hence naturally stratigraphical breaks occur at different horizons in different places, although they are really all effects of the same cause. A clearer grasp of this principle would make for lucidity in many tectonic discussions.

GEOLOGY OF CALIFORNIA. By RALPH D. REED. pp. xxiv + 350, 60 figs. and relief map. American Association of Petroleum Geologists, Tulsa, Oklahoma, 1933. Price 5 dollars.

THE development of the Californian oilfields during the last thirty years has led to the accumulation of an enormous volume of accurate information concerning the underground geology of the State. As a result of this, many of the previously accepted ideas of the structure and stratigraphy in the area affected must be modified or radically altered ; it has been impossible, however, for those who are not intimately concerned with Californian geology to realize the great advances which have been made, since most of the work has been published in a multitude of scattered papers. Dr. Reed has succeeded in reducing this unwieldy amount of recent literature to a readable and very welcome summary of Californian geology. The book is written from the point of view of a Coast Range geologist, and naturally gives most attention to post-Jurassic events.

The earlier views on the structure and orogeny of the Coast Ranges have suffered considerable modification. The theory of persistent and independent fault blocks has not stood up to the test of accurate oilfield mapping, and there is not, at present, a single clearly proved example of such a structure in the Coast Range belt. Careful field work has everywhere shown that the structures of palaeogeographical importance are primarily folds. The main Tertiary orogeny took place early in the Pleistocene, and this was the first period of important diastrophism since the folding of the Sierra Nevada in the later Jurassic. Nearly all the faults and important thrusts are of Pleistocene age, and most of the folds which affect post-Jurassic rocks had their maximum movement at this time. There is consequently an unusually fine development of folded marine Pleistocene sediments exposed in south-western California; the rocks vary from coarse conglomerates to fine foraminiferal " chalk ", and reach a thickness of 2,500 feet.

Researches on the ecology of the foraminifera have led to results of considerable stratigraphical importance. A large proportion of the Pleistocene species is still living, and the ecological groups of which they form part may be traced back through the Pleistocene into the later Tertiary. By making use of the present-day ecology of the benthonic foraminifera it has been possible to work out the variations in depth and salinity of the water which accompanied the changes in facies of the sediments. A suggestive result of such work is the indication it gives of a comparatively deep-water facies of coarse detrital deposits (conglomerates and sandstones) amongst the Coast Range sediments. In the Pliocene of southern California, particularly, there are considerable thicknesses of such rocks, interbedded with shales containing foraminifera characteristic of depths between 600 and 3,000 feet. These sediments appear to have been laid down in long, narrow, and steep-sided troughs.

Petrological investigations of the Cretaceous and Tertiary sandstones of the Coast Ranges have shown that these rocks are largely felspathic, and a genuine quartz sandstone is a rare thing, calling for a special explanation. The felspars usually make up about 50 per cent of the rock, but some formations contain over 70 per cent. A number of these rocks are known to have been formed under humid conditions, and we are again forcibly reminded that a high proportion of felspar does not necessarily indicate sedimentation of desert waste.

M. B.

RONAY: A DESCRIPTION OF THE ISLANDS OF NORTH RONA, ETC. By MALCOLM STEWART. pp. 74, with 33 figs. Oxford University Press, and London, Humphrey Milford, 1933. Price 7*s.* 6*d.*

THIS book, as its sub-title denotes, consists of a description of those remote and little-known islands of the north-west coast of Scotland, which are called North Rona or Ronay, Sula Sgeir, and the Seven Hunters or Flannan Islands, with an account of their history, geography, natural history, and geology. The author visited each of these islands and the description of his own observations and impressions gives an additional interest to the book. It is illustrated by a series of photographs, all of which are good, and some of which are excellent, those of the gannets on Sula Sgeir being particularly pleasing. There are also some useful maps besides illustrations showing the lighthouse on Eileen Mor and the remains of the chapel on North Rona and other features of interest.

In the account of the natural history the author had the help of Mr. T. H. Harrisson, who supplied the lists of the resident and migratory birds. Coming to the geology, it is shown that all the islands consist of hornblende-gneiss with pegmatitic veins. The presence of pieces of rock alien to the islands on North Rona and Sula Sgeir suggest that they came under the influence of the Quaternary ice as supposed by the late James Geikie, while the existence of a deposit of cemented sand on North Rona is regarded as evidence of a raised beach. The work is provided with a good bibliography.

F. H. A. M.

VERTEBRATE PALAEONTOLOGY. By Professor A. S. ROMER. pp. viii + 491. With 358 figures. University of Chicago Press, Illinois, and Cambridge University Press, 1933. Price 22*s*. 6*d*.

THIS work is written on somewhat original lines. It not merely gives an account of vertebrate history as revealed by the fossil record, treating the phylum group by group with a summary of the faunal succession as found in the rocks, but it describes each main type or order where possible in the light of its nearest living representatives, having regard to their conditions of existence and physiological reactions. The result is that the book makes a wider appeal than is customary in treatises on palaeontology and there is no other modern work in English which covers the same ground. At the same time it should be none the less useful as a textbook for employment in organized courses of study.

The Vertebrata are here held to include the Cyclostomata and the primitive fossil genera belonging to the orders Heterostraci, Osteostraci, and Anaspida, and the problematical genus *Palaeospondylus*. These are grouped together in the class Agnatha, or jawless vertebrates, and are placed at the bottom of the super-class Pisces. The other three classes of fishes are the Placodermi, the Chondrichthyes, and the Osteichthyes. The other great vertebrate super-class Tetrapoda comprises the well-known classes of Amphibia, Reptilia, Aves, and Mammalia. This classification has the merit of simplicity if it fails to stress the fundamental distinction between cyclostome and gnathostome. After an introductory chapter the principal groups are successively reviewed. Nearly half the work is devoted to the mammals, but in view of their general interest and the culmination of the class in man, this calls for no apology in an elementary textbook. There is an excellent final chapter on the Primates embodying an account of the latest discoveries of Pleistocene man. Reference to recent investigations in the various fields of study are duly included, and the book is generally up-to-date. Moreover, it is very readable and the illustrations are well-chosen, clear, and helpful. The account of the development of the Equidae and of their specialization in response to changing conditions in recent times is a model of lucidity. The bibliography which is arranged according to the successive zoological groups contains 314 references.

F. H. A. M.

REPORTS AND PROCEEDINGS.

The Council of the Geological Society of London have announced their annual list of Medals and Awards as follows :—

The Wollaston Medal to Sir Henry Alexander Miers, M.A., D.Sc., F.R.S., Honorary Professor of Crystallography in the University of Manchester, for his researches on the mineral structure of the earth and especially in the realms of crystallography and mineralogy.

The Murchison Medal to Professor George Hickling, D.Sc., Professor of Geology in Armstrong College, Newcastle-on-Tyne, for his contributions to geological science in many branches and especially in the stratigraphy of the Coal Measures and the structure of coal.

The Lyell Medal to Dr. Finlay Lorimer Kitchin, M.A., F.R.S., of H.M. Geological Survey, in recognition of the value of his contributions to palaeontological science.

Another Lyell Medal to the Rev. Walter Howchin, formerly Professor of Geology and Palaeontology in the University of Adelaide, South Australia, for his geological and palaeontological researches in Australia, and particularly for his investigations of ancient glacial deposits.

The Wollaston Fund to Dr. William Richard Jones, M.Inst.M.M., of the Royal School of Mines, in recognition of the value of his work in economic geology and his recent investigations on silicosis.

The Murchison Fund to Dr. John Wilfrid Jackson, Assistant Keeper in the Manchester Museum, for his contributions to Pleistocene geology and palaeontology and to malacology.

The Lyell Fund to Mr. Frederick William Shotton, M.A., in recognition of the value of his work on the Upper Palaeozoic and Quaternary rocks of the Midlands.

CORRESPONDENCE.

DISTURBED GLACIAL BEDS IN DENMARK.

SIR,—I have only just discovered by mere chance that Mr. George Slater published a letter under the title of " Disturbed Glacial Beds in Denmark ", bearing date 8th February, 1932, in THE GEOLOGICAL MAGAZINE, 1932, LXIX, 143–4. Mr. Slater has not taken the trouble to send copies either to Mr. Axel Jessen or to me. This letter obliges me to put forward the following remarks : Mr. Slater writes, " Far from objecting to the publication of my views, Dr. Madsen, as Director of the Survey, wrote in April, 1926, to say that he had read the MS. of my paper with the greatest interest and that he had tried unsuccessfully to secure funds for its publication in Denmark, but intended to make another attempt. Again, in May, 1926, Dr. Madsen stated that he could not get the paper printed in Denmark, but that I ought to publish it in England. No objection was raised by Dr. Madsen on the grounds that I should be anticipating Danish work." This may look as if I have expressed my approval of the correctness of Mr. Slater's observations and conclusions, set forth in the named paper. I have not done so at all. When Mr. Slater at the time sent me his MS. and urgently begged me to get it printed in Denmark, I found the theory which he sets forth in it, that the disturbed and dislocated Quaternary deposits in the cliffs represent the final position of englacial material after the melting of the interstitial ice, to be so original and of such general scientific interest, that for that reason alone his paper deserved to be published—although I could not concur in Mr. Slater's opinion that the dislocations in Lönstrup Cliff and other similar Danish cliffs were produced in this manner. But of course I did not check the details of Mr. Slater's paper, nor did I examine the correctness of his observations, the view I held being that this was no concern of mine, and thus I have taken upon myself no responsibility at all for the errors which Mr. Slater has committed, and which are pointed out by Mr. Axel Jessen. Mr. Slater's work at Lönstrup Cliff has only been superficial. He cannot have made many ascents of the cliff to examine and measure the upper parts of it, nor dug out the overthrust planes and studied them in their details, nor taken many measurements, hence the many mistakes in his paper.

I raised no objections to Mr. Slater's work anticipating Mr. Jessen's because I held the view that it was best that Mr. Slater's publication should come before that of Mr. Jessen, for then the latter could define his attitude to Mr. Slater's theory in his standard work on Lönstrup Cliff (Axel Jessen, *Lönstrup Klint*, Danmarks geologiske Undersögelse. II. Række, Nr. 48. Köbenhavn, 1931. With an English Summary, and an Atlas), and would not have to make another publication after that of Mr. Slater. And besides, I assumed that Mr. Slater was in accord with Mr. Jessen as to the publication of his paper, a reasonable supposition, I think, as Mr. Jessen, who has worked at the cliff for more than thirty-five years, in the course of two days in 1925 went over the Lönstrup Cliff with Mr. Slater and gave him all the information he wanted concerning the geology of the cliff, and informed Mr. Slater that he was going to publish a description with a horizontal section of the whole cliff.

VICTOR MADSEN.